

A STUDY TO ANALYZE AND DEVELOP DESIGN CRITERIA FOR A FLIGHT - CONCEPT PROTOTYPE VAPOR DIFFUSION WATER RECLAMATION UNIT

By Henry Kolnsberg and Melvin Stoltz

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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
SUMMARY	1
INTRODUCTION	3
DEVELOPMENT AND EVALUATION OF A MATHEMATICAL MODEL	5
Objectives	5
Theoretical Model	5
Mechanism	5
Experimental Apparatus	9
Module Description	9
Module Assembly	11
Experimental System	11
Experimental Objectives	14
Model Verification	14
Experimental Results	16
Gap Width Variations	16
Gap Gas Composition	16
Vapor Pressure as the Driving Force - Tests 6-9, 17-19.....	20
Effects of Gap Gas Pressure and Effect of Urine	
Recirculation Rate - Tests 10-16	20
Conclusions.....	24
EXPERIMENTAL EVALUATION OF SELECTED SECONDARY	
PARAMETERS	25
Modular Flow Arrangements - Series And Parallel Urine Flow	25
Non-Recurring Urine Flow	25
Maximum Recovery.....	28
Batch vs Continuous Feed	28
Conclusions.....	31
MICROBIOLOGICAL STUDY	33
Objectives	33
Rationale of Inherent Microbiological Safety In The	
Vapor Diffusion System	33
Chemical Treatment	34
Pasteurization.....	34
Distillation.....	34
Filtration	34
Sterilization	34
Test Procedures	35
Results	35
Conclusions.....	37
MEMBRANE STUDY.....	39
Objectives	39
Study Approach	39
Experimental Objectives	39

TABLE OF CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
Description of Experiments	40
Results	40
Conclusions	47
DESIGN STUDIES	51
Objectives	51
Discussion	51
Flight System Description	51
Diffusion Still Assembly	53
Condensers	55
Evaporators	55
Concentration Sensor	55
Design Optimization	59
Heater Location	59
Recirculation Flow Rate	59
Operating Parameters	59
Optimization Conclusions	62
System Comparison	67
Ground Rules	67
System Design	67
Growth Potential	72
Recovery Efficiency	72
Reduction of Expendables	72
Alternate Use	72
SAMPLE CALCULATIONS	75
REFERENCES	81

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	Schematic Representation of the Vapor Diffusion Water Reclamation Mechanism	6
2	Cross Section of Diffusion Still Module - Schematic	10
3	Diffusion Still Module - Disassembled	12
4	Experimental System - Schematic	13
5	Processing Rate as a Function of Diffusion Gap Width	18
6	Diffusion Constants as a Function of Gap Width	19
7	Processing Rate as a Function of Evaporator Tempera- ture	21
8	Overall Diffusion Constant as a Function of Vapor Pressure Differential	21
9	Processing Rate as a Function of Urine Recirculation Rate and Gap Pressure	22
10	Overall Diffusion Constant as a Function of Urine Recircu- lation Rate and Gap Pressure	23
11	System Arrangement for Series and Parallel Flow - Schematic	26
12	Processing Rate as a Function of Time for Parallel and Series Urine Flow Through the Modules with Continuous Urine Feed	27
13	Processing Rate as a Function of Urine Solids Concentra- tion	29
14	Processing Rate as a Function of Time for Urine Batch Feed	30
15	Membrane Test Set-Ups - Schematic	43
16	Water Processed as a Function of Time for the Three Best Membranes	44

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
17	PVC Membrane Processing Rate as a Function of Exposure Time	45
18	Processing Rate as a Function of Urine Temperature for the Three Best Membranes	46
19	PVC Constant Pressure Differential Test Set-Up - Schematic	48
20	Flight Concept Vapor Diffusion Water Reclamation System	52
21	Prototype Diffusion Still Assembly	54
22	Prototype Condenser	56
23	Prototype Condenser Pressurization Arrangement	57
24	Prototype Evaporator	58
25	Membrane Area as a Function of Diffusion Gap Width for Specific Temperature Combinations	61
26	Total Losses as a Function of Diffusion Gap Width for Various Evaporating Temperatures	63
27	Total Heat Required as a Function of Heating Fluid Temperature	65
28	Total Heat and Membrane Area as a Function of Condensing Temperature	66
29	Four-Man System Performance Flow Chart	70
30	Compressor Power as a Function of Membrane Area	74
31	Evaporator Differential Temperature as a Function of Total Heat	76
32	Water Vapor Pressure as a Function of Urine Temperature for Specific Solids Concentrations	78

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
33	Specific Gravity of Urine as a Function of Solids Concentration.....	79
34	Saturated Vapor Pressure as a Function of Condensing Temperature	80

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
I	Nominal Test Run Conditions.....	15
II	Experimental Test Data	17
III	Effect of Helium as Inert Gap Gas	20
IV	Non-Recirculating Urine Test Data	28
V	Membrane Investigation Data for Urine Compatibility and Water Vapor Permeability.....	41
VI	Diffusion Gap Width Effect on Evaporator Area and Heat Loss	64
VII	Total Penalty for Various Gap Widths for a Low Heating - Cooling Penalty	64
VIII	Total Penalty for Various Gap Widths for a High Heating - Cooling Penalty	64
IX	Vapor Diffusion Water Reclamation System Weight and Volume Estimates.....	68
X	System Weight and Penalty Summary - 500 Day Mission	69
XI	System Weight and Penalty Summary.....	71

A STUDY TO ANALYZE AND DEVELOP DESIGN
CRITERIA FOR A FLIGHT-CONCEPT PROTOTYPE
VAPOR DIFFUSION WATER RECLAMATION UNIT

By Henry Kolnsberg and Melvin Stoltz

Hamilton Standard

A Division of United Aircraft Corporation

Windsor Locks, Connecticut

SUMMARY

1. The VDR unit successfully completed a duration test of 54 days. This conclusively proves the concept practical for water reclamation on board space crafts.
2. Design of a simple, maintainable unit for 95% recovery is possible as shown in this report. Such a concept, with reasonable membrane development, would have the lowest fixed and expendable weight of any water reclamation system now under consideration.
3. The VDR can recover over 98% of the available water if a precipitate-solids filter is added to the system. Such potential was demonstrated during test when 98% recovery was achieved. In this case, the batch tank acted as a settling place for solids. The system can operate with solids in the recirculation loop.
4. The various design parameters investigated during this phase have been proven to be analytically predictable, once the membrane performance has been determined empirically.
5. The porous plate condensor concept has been proven by 5000 hr of accumulated operation during prototype testing.
6. The VDR concept is an inherent bacteria-free water producer including failsafe design for membrane failures.
7. Future work recommendations: (a) development of a structurally sound membrane; (b) system operation at a high solids content-filtration of solids; (c) design and construction of a prototype system.

INTRODUCTION

Several water reclamation systems for space vehicle use have been proposed and operationally demonstrated. The more successful approaches have involved various distillation concepts which still suffer from the complexity, power, and reliability problems associated with the stringent demands of producing chemically-pure and bacteria-free water.

A simple, more promising variation of waste water reclamation by distillation principles is utilized by the Hamilton Standard membrane vapor diffusion system (VDR) conceived in early 1965. A prototype of this system was built under contract NAS-1-5312 with the NASA Langley Research Center, entitled "The Research and Development of an Improved Water Reclamation System By a Phase-change Technique," and was successfully demonstrated. The system is original in its use of a semi-permeable membrane as a phase separator between liquid and vapor in the evaporation phase of the distillation process. It achieves true zero gravity capability through a unique application of a porous plate as a condenser-water separator requiring no moving parts.

Further examination and development of the concept to establish system design criteria formed the basis for the subsequent contract to which this report addresses itself. At the start of this phase the VDR had two serious drawbacks:

1. Maximum demonstrated membrane life was 120 hr
2. Cellophane, which was the originally tested membrane, could not be easily fabricated into a replaceable module.

In addition, experimental verification of the mathematical model of operation was required.

As a result of this contract phase, significant improvements toward realization of a flight system have been achieved. Of major significance was the discovery of a bondable membrane which demonstrated over 50 days of continuous operation, its life being limited by membrane structural quality rather than an inherent life.

Comparative projections of the membrane vapor diffusion system show it to have a potential advantage over other water reclamation systems now being considered. Further development effort should be aimed at greater improvements in system operability, functional performance, and quality of membranes employed. From the results of this contract phase, it is estimated that the time and expenditure required to develop a flight VDR would be equal to or less than any other water reclamation system.

DEVELOPMENT AND EVALUATION OF A MATHEMATICAL MODEL

Objectives

The objectives of this section of the report are:

1. Development of a physical description and mathematical model of the vapor diffusion process.
2. Verification of this model by experimentation.

To obtain these objectives a physical description of the vapor diffusion process is proposed in the Theoretical Model section and a mathematical description of this model derived to show how processing rate depends upon flows, temperatures, compositions, and physical dimensions.

A description of the experimental apparatus follows, with special emphasis on possible deviations from the mathematical model.

The experiments required to confirm the validity of this model are outlined specifically in Experimental Objectives. Later in the same section nominal operating points for the experimental runs are presented.

The experimental results are subsequently tabulated and interpreted.

Theoretical Model

Mechanism. - Since the VDR process requires heat equal to the heat of vaporization of water and transfers water from the liquid phase into a vapor phase, it is obvious that evaporation is an important part of the process.

The ultimate separation mechanism is believed to be (1) vaporization of water at the liquid-membrane interface, (2) diffusion of water through the membrane, and (3) diffusion of water vapor through the inert gas in the vapor gap.

Fig. 1 depicts this mechanism and also shows the heat transfer mechanisms which become important in secondary parameter studies. Meaningful study of the fundamental diffusion mechanism requires adequate heat transfer and a homogeneous urine composition so that the two diffusion processes actually limit, or "control", the processing rate.

Note that the ambient pressures anywhere in the system are not of great importance. It is only required that the urine be pressurized to keep it from boiling, and that the cooling fluid be cold enough to condense the water at the ambient vapor gap pressure. In-

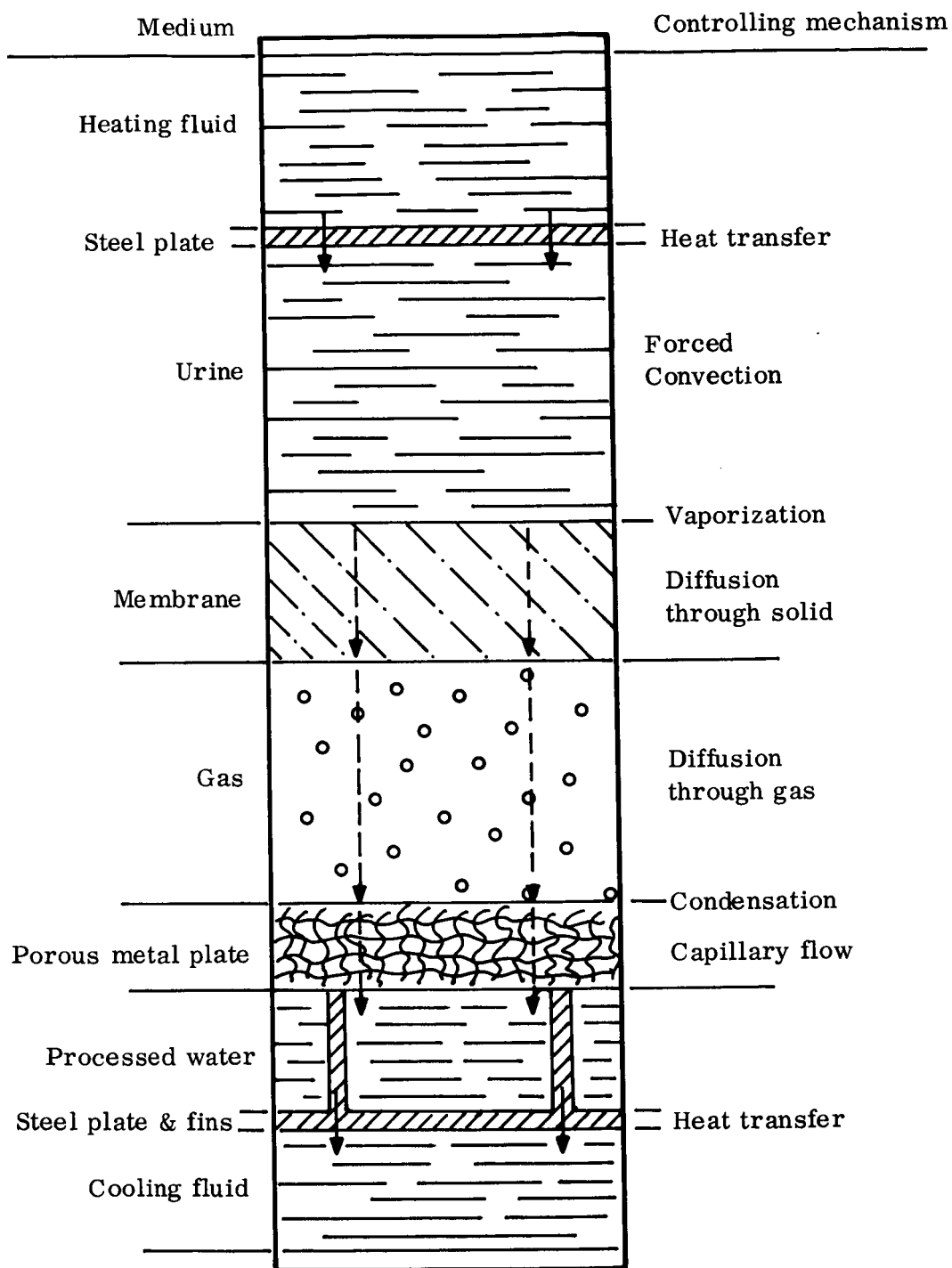


Figure 1. Schematic Representation of the Vapor Diffusion Water Reclamation Mechanism

practice the urine was held at atmospheric pressure and the vapor gap slightly (3 in. Hg) above atmospheric pressure. This helped hold the membrane in place, kept urine out of the condensate if the membrane ruptured, and facilitated collection of the water from the porous plate.

Mathematical description. - The driving potential of the system is the water vapor partial pressure gradient which results from the temperature differential between the heated urine and the condenser surface. Appreciable resistance to the mass transfer of water vapor exists through the membrane and across the diffusion gap.

The membrane impedance is defined by the empirical membrane permeability constant K_m , which relates the rate of flow R_m to the pressure drop across the membrane:

$$R_m = K_m A_e (p_1 - p_2) \text{ (ref. 1) } (1)$$

where A_e is the effective membrane area, ft^2

p_1 is the water vapor partial pressure in the brine, lb/in.^2

p_2 is the water vapor partial pressure on the diffusion gap side of the membrane lb/in.^2

R_m is the rate of flow through the membrane, lb/hr

K_m is the permeability constant, $\text{lb/hr-ft}^2\text{-psi}$

The diffusional flow of water vapor through a non-condensable gas is described by the following one dimensional diffusion equation:

$$R_g = \frac{D A_d P_t (p_2 - p_3) M}{R_o T P_{gm} Z} \text{ (ref. 2) } (2)$$

where R_g is the diffusion rate, lb/hr

D is the diffusivity of water vapor through the gas, ft^2/hr

A_d is the diffusional cross sectional area, ft^2

P_t is the total pressure, lb/ft^2

p_2 is the partial pressure of water at the vapor side of the membrane, lb/ft^2

p_3 is the partial pressure of water at the condenser, lb/ft^2

M is the molecular weight of water, lb/mole

R_o is the universal gas constant, 1543 lb-ft/mole-°R

T is the average gap temperature, °R

P_{gm} is the log mean partial pressure of the inert diffusion medium, lb/ft²

Z is the gap width, ft

The diffusivity, D, of the water vapor through a gas is calculated by the following equation:

$$D = BT^{3/2} \left(\frac{1}{M_1} + \frac{1}{M_2} \right)^{1/2} \quad (\text{ref. 3}) \quad (3)$$

$$\text{where } B = \left\{ 10.7 - 2.46 \left(\frac{1}{M_1} + \frac{1}{M_2} \right)^{1/2} \right\} \times 10^{-4}$$

T = absolute temperature, (°K)

M_1, M_2 = molecular weights of components 1 and 2

P = absolute pressure (atmospheres)

r_{12} = collision diameters (angstroms)

$$= \frac{(r_o)_1 + (r_o)_2}{2}$$

$$r_o = 1.18 V_o^{1/3}$$

V_o = molal volume of liquid at normal boiling point (cc/gram-mole)

I_D = collision integral for diffusion function of $\frac{KT}{E_{12}}$

$$\frac{E_{12}}{K} = \left[\left(\frac{E_1}{K} \right) \left(\frac{E_2}{K} \right) \right]^{1/2}$$

K = Boltzmann's constant - 1.38×10^{-6} ergs/°K

E_{12} = energy of molecular interaction (ergs)

Equation (2) can be put in the form of equation (1) by letting

$$K_g = \frac{D P_t M}{R_o T P_{gm} Z}$$

thus

$$R_g = K_g A_d (p_2 - p_3) \quad (4)$$

Since

$$R_g = R_m \text{ and } A_e = A_d,$$

equations (1) and (3) may be combined to eliminate p_2 , giving

$$R = K_T A (p_1 - p_3)$$

where

$$\frac{1}{K_T} = \frac{1}{K_g} + \frac{1}{K_m}$$

when

$$K_T = \text{total diffusivity constant, } \frac{\text{lb/hr}}{\text{ft}^2 \text{ psi}}$$

To verify this model, the experimental work was first devoted to determining K_m . This was determined by finding K_T as $K_T \rightarrow K_m$, i.e., the extrapolated value for K_T at zero diffusional gap.

K_T was then predicted by combining the theoretical value of K_g and the experimental value for K_m at several gap spacings, and this prediction compared to the experimental values.

The successful comparison shown later in this report tends to confirm the above analysis as correct.

Experimental Apparatus

Module description. - A schematic of the actual diffusion still cross section is shown in fig. 2. Starting at either end, the module consists of the following elements:

- a) Heating fluid flow passage
- b) Urine flow passage

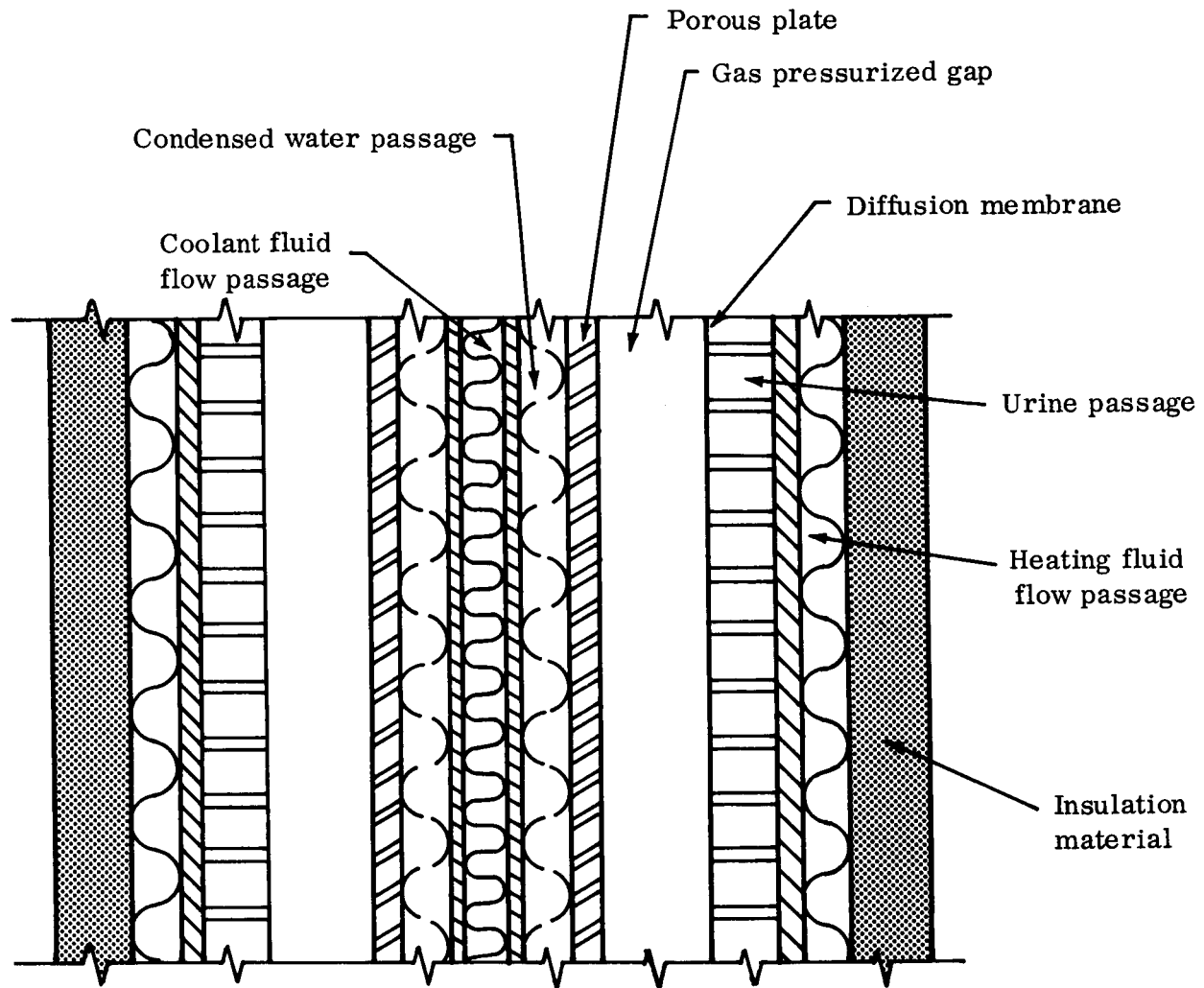


Figure 2. Cross Section of a Diffusion Still Module - Schematic

- c) Semi-permeable diffusion membrane
- d) Vapor diffusion gap
- e) Porous metal plate condensing surface
- f) Product water collection passage
- g) Coolant fluid flow passage

Urine, pretreated with chromic acid to prevent ammonia formation, is continually circulated through the urine passages, and heated to the desired operating temperature by the heating fluid. The water vapor from the urine passes into the porous structure of the semi-permeable membrane and diffuses from the opposite membrane surface through the diffusion gap. After diffusion through the gas in the gap, the water condenses on the surface of the porous plate. The gap gas, which was supplied from a storage cylinder, was maintained at a pressure slightly above the ambient pressure but lower than that necessary to bubble gas through the porous plate, forcing the condensed water through the porous plate into the product water collection passage and then to potable water storage. Nitrogen was used as gap gas in all test except one in which helium was used.

Module assembly. - A complete module, built at Hamilton Standard under Contract No. NAS 1-5312 and used in this program, is shown disassembled in fig. 3. The basic system consists of two parallel evaporators having a common condenser between them. The evaporator provides a means of supporting and sealing the membrane, maintaining a flow of urine beneath the membrane, transferring heat to the urine and maintaining a diffusion gap of uniform width. A polyvinylchloride gasket, which provides a sealing surface between the membrane and the condenser flange, is shown in place on the evaporator flange. This gasket also helps to minimize the heat losses between the hot evaporator and the cold condenser and controls the width of the diffusion gap.

The condenser consists of a cooling fluid passage and two porous plates on which the water vapor condenses and through which the condensed water passes into a collection passage and eventually into a storage tank. The pore size of the porous plates has been selected so that the differential pressure used in the gap is insufficient to break the liquid surface tension. This assures passage of the water and retention of the inert gas in the vapor gap. The water transfer capacity of the plates greatly exceeds the amount of water that could be produced by the evaporator.

Experimental system. - The experimental system is shown in fig. 4. A hot water bath and urine supply were placed outside the module and the fluids circulated to it with small pumps. The urine flow was in series from one side of the dual module to the other. Tap water was used for condenser cooling.

The experimental system provided a good basis for examination of the mathematical model, because

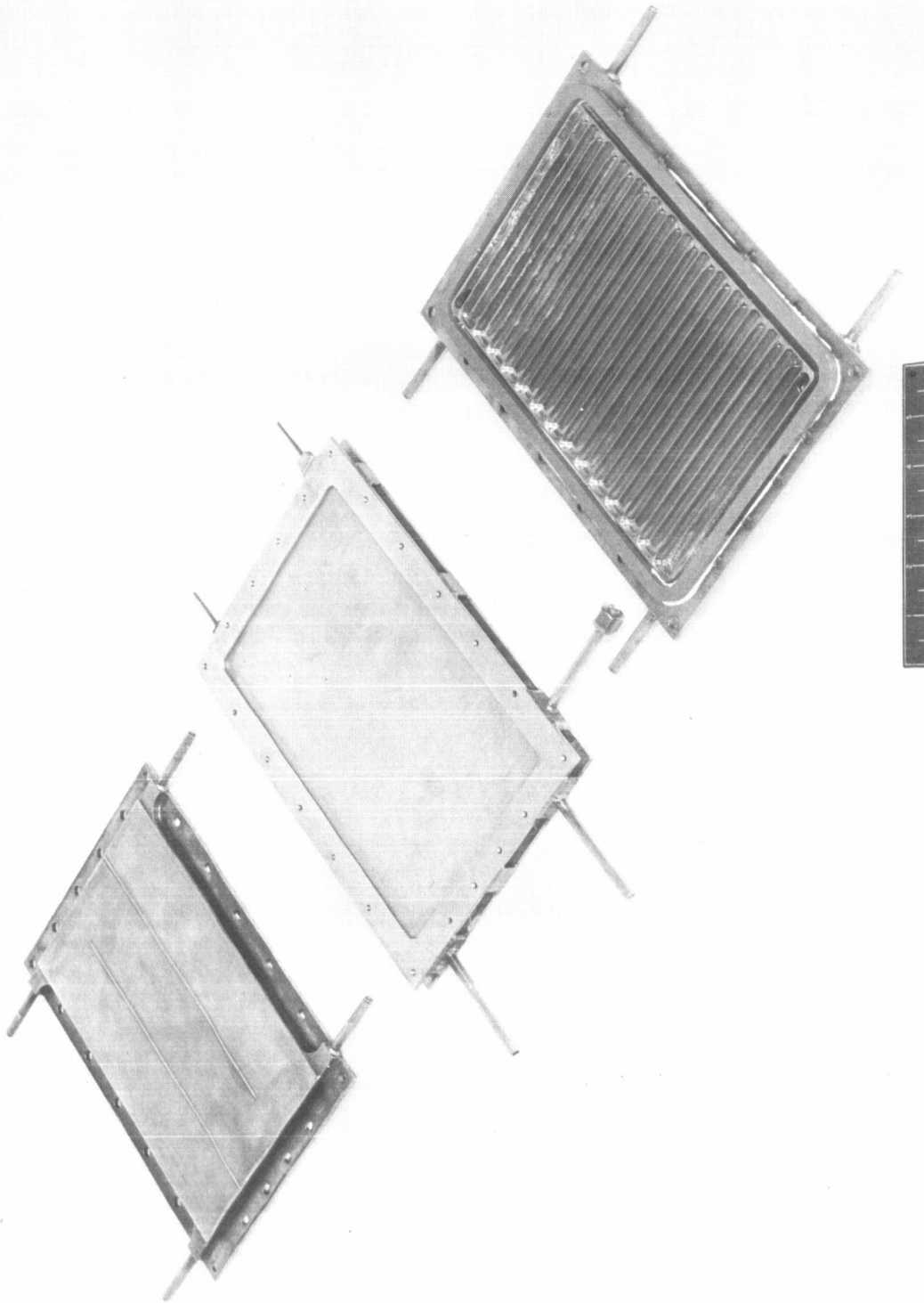


Figure 3. Diffusion Still Module - Disassembled

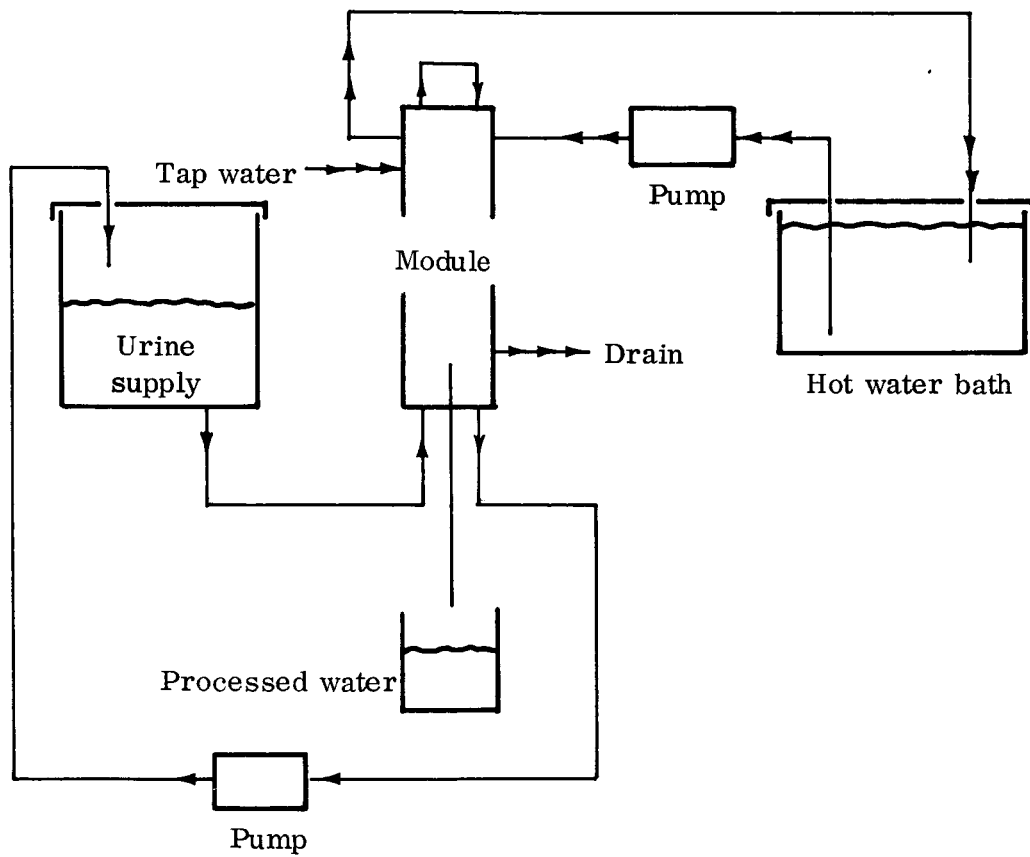


Figure 4. Experimental System - Schematic

- a) The heating fluid velocity was high enough to prevent development of a significant temperature gradient across the passages or along them. This was known to be the case from previous work.
- b) The condensing area was large enough so that no significant temperature gradient existed across the porous plate. This was also known to be the case from previous work.
- c) Brine recirculation was such that the temperature was reasonably constant, and there was no appreciable concentration gradient across or along the passages. This presumption was experimentally verified, as explained later in this report.
- d) The feed method was such that the changes in urine concentration did not result in significant changes in water vapor partial pressure. Periodic replenishments of urine and monitoring of urine specific gravity assured this.

Experimental Objectives

Model verification. - To verify the mathematical model, the following objectives were established:

- a) Experimental determination of K_m , the membrane permeability constant.
- b) Experimental determination of K_t , the total diffusion constant, over a range of its most important variables--the membrane gap and the molecular weight of the inert gas through which diffusion takes place; and comparison of the experimental K_t with a theoretical value.
- c) Confirmation that the driving force for processing rate is indeed the water vapor partial pressure differential between the heated urine and the porous plate condenser.

To confirm that the urine velocity was adequate, an additional objective was established:

- d) Determination of the effect of urine recirculation rate on processing rate.

In addition, confirmation of the unimportance of small diffusion gap pressure variations was desired, resulting in another objective:

- e) Determination of the effect of small changes in gap pressure on processing rate.

Table I gives the nominal values of the experimental variables for the test runs and relates them to the above objectives.

TABLE I
NOMINAL TEST RUN CONDITIONS

Objective number	Run number	Gap spacing, in.	Urine temperature, °F	Urine flow rate, ml/min	Gap pressure in. Hg	Condensing temperature, °F	Gap gas
1.2	21	0.005	145	200	3	70	N ₂
1.2	22	0.055	145	200	3	70	N ₂
1.2	23	0.125	145	200	3	70	N ₂
2	24	0.125	145	200	3	70	N ₂
2	25	0.125	145	200	3	70	He
3	6	0.125	125	200	3	70	N ₂
3	7	0.125	135	200	3	70	N ₂
3	8	0.125	145	200	3	70	N ₂
3	9	0.125	155	200	3	70	N ₂
3	17	0.125	145	200	3	60	N ₂
3	18	0.125	145	200	3	70	N ₂
3	19	0.125	145	200	3	100	N ₂
4	10	0.125	145	50	3	70	N ₂
4	11	0.125	145	100	3	70	N ₂
4	12	0.125	145	200	3	70	N ₂
4	13	0.125	145	300	3	70	N ₂
5	14	0.125	145	200	2	70	N ₂
5	15	0.125	145	200	3	70	N ₂
5	16	0.125	145	200	4	70	N ₂

Experimental Results

Table II gives the actual parameters and results for the experimental tests of EXPERIMENTAL EVALUATION OF SELECTED SECONDARY PARAMETERS. Sample calculations for the computed values are provided in the appendix.

Gap width variations. - Tests 21, 22, and 23 show the change in K_t , the total diffusion constant, as gap width was varied over a range of 0.005 to 0.125 in. Other parameters were held constant. Results are plotted in fig. 5.

Fig. 6 shows the diffusion constants for these tests, K_t (exp.). Since the membrane diffusion constant K_m equals K_t at zero gap, a slight extrapolation of the experimental curve (K_t (exp)) of fig. 6 gives $K_m = 0.323$ lb/hr-ft²-psi. This figure is in excellent agreement with the previously estimated value for membrane coefficient of 0.320 lb/hr-ft²-psi (ref. 4).

A theoretical value for K_g can be predicted by the previously introduced equation:

$$K_g = \frac{D}{R_o} \frac{P_t}{T} \frac{M}{P_{gm} Z}$$

These values are tabulated in table II and also plotted in fig. 6. When combined with K_m in the usual manner

$$\frac{1}{K_t} = \frac{1}{K_g} + \frac{1}{K_m}$$

the resultant K_t (calc.) conforms reasonably well with the experimental data. Later tests, not shown here because of slightly off-standard operating conditions, indicate that the experimental value of K_t (exp.) at 0.125-in. gap width determined in test 23 is high. It will in fact be shown that the value for K_t (exp) is constant at a value of about 0.16 lb/hr-ft²-psi, changing only with gap width and gap gas composition.

Gap gas composition. - Tests 24 and 25 were run at similar conditions (table I), except that helium was substituted for nitrogen as the inert gap gas in test 25. Table III compares the experimental and calculated values for K_t , the total diffusion constant. The experimental values are higher than theoretical, but quite satisfactory when the very fundamental basis for the theoretical gap diffusion constant calculation is considered.

Note that the use of helium virtually eliminates the gap gas as a controlling resistance to diffusion. If helium is used, further improvement in rate will depend upon development of a more permeable membrane.

TABLE II
EXPERIMENTAL TEST DATA

		TEST DATA										CALCULATED VALUES					
Parameter varied	Run number	Urine inlet temperature - °F	Urine outlet temperature - °F	Urine flow rate - ml/min	Gap pressure in. Hg	Condenser temperature - °F	Processing rate - ml/hr	Urine outlet specific gravity	Water through membrane - ml	Conductivity mhos/cm	Remarks	Evaporating temperature - °F	Evaporating part. press. - psi	Condensing part. press. - psi	Differential pressure - psi	Total diffusion constant lb/hr ft ² psi	Gap diffusion constant lb/hr ft ² psi
Gap width	21	132	144	200	3.0	73	280	1.025	1200	125	0.055 in.	140.5	2.93	0.40	2.53	0.308	6.63
	22	132	141	210	2.9	69	200	1.050	1100	210	0.055 in.	138.4	2.77	0.35	2.42	0.230	0.800
	23	132	142	200	3.1	69	165	1.050	800	270	0.125 in.	138.7	2.80	0.35	2.45	0.188	0.450
Gap gas	24	137	152	180	2.4	68	210	1.035	600	90	N ₂	147.2	3.38	0.34	3.04	0.192	0.472
	25	139	152	200	2.3	77	295	1.055	1700	100	He	148.5	3.41	0.46	2.95	0.278	1.99
Urine temp.	6	121	127	220	4.3	67	90	1.045	3800	175		125.2	1.95	0.33	1.62	0.155	0.298
	7	131	139	250	2.7	73	130	1.025	2100	325		136.4	2.63	0.40	2.23	0.162	0.326
	8	141	151	260	4.7	70	195	1.025	1500	310		147.8	3.52	0.36	3.16	0.171	0.364
	9	150	160	270	5.0	74	255	1.020	1000	165		157.2	4.43	0.41	4.02	0.179	0.418
Condenser temp.	17	141	154	230	2.2	64	185	1.060	4200	175		147.6	3.50	0.30	3.20	0.161	0.322
	18	142	157	210	3.4	72	200	1.050	2200	250		152.0	3.90	0.39	3.51	0.158	0.310
	19	142	157	215	4.0	102	160	1.055	2600	300		151.3	3.84	1.01	2.83	0.157	0.306
Urine flow	10	140	150	50	1.0	66	185	1.085	1700	150		147.8	3.52	0.32	3.20	0.161	0.322
	11	133	157	100	5.6	74	220	1.060	1100	260		148.6	3.59	0.42	3.17	0.180	0.417
	12	139	151	215	4.0	72	170	1.055	7800	285		147.3	3.47	0.39	3.08	0.154	0.294
	13	141	151	290	3.6	72	175	1.060	7300	225		147.5	3.49	0.39	3.10	0.157	0.307
Gap pressure	14	136	148	200	2.2	72	170	1.035	4200	180		141.6	2.93	0.39	2.54	0.185	0.435
	15	134	146	210	32.0	68	165	1.030	3600	165		141.4	2.99	0.34	2.65	0.173	0.373
	16	138	148	220	4.2	69	175	1.025	700	230		144.6	3.24	0.35	2.89	0.168	0.351

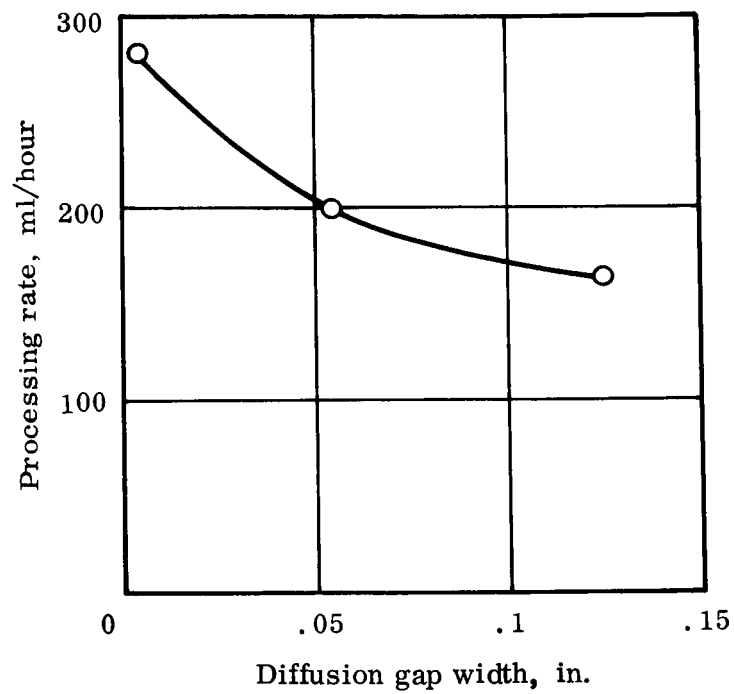


Figure 5. Processing Rate as a Function of Diffusion Gap Width

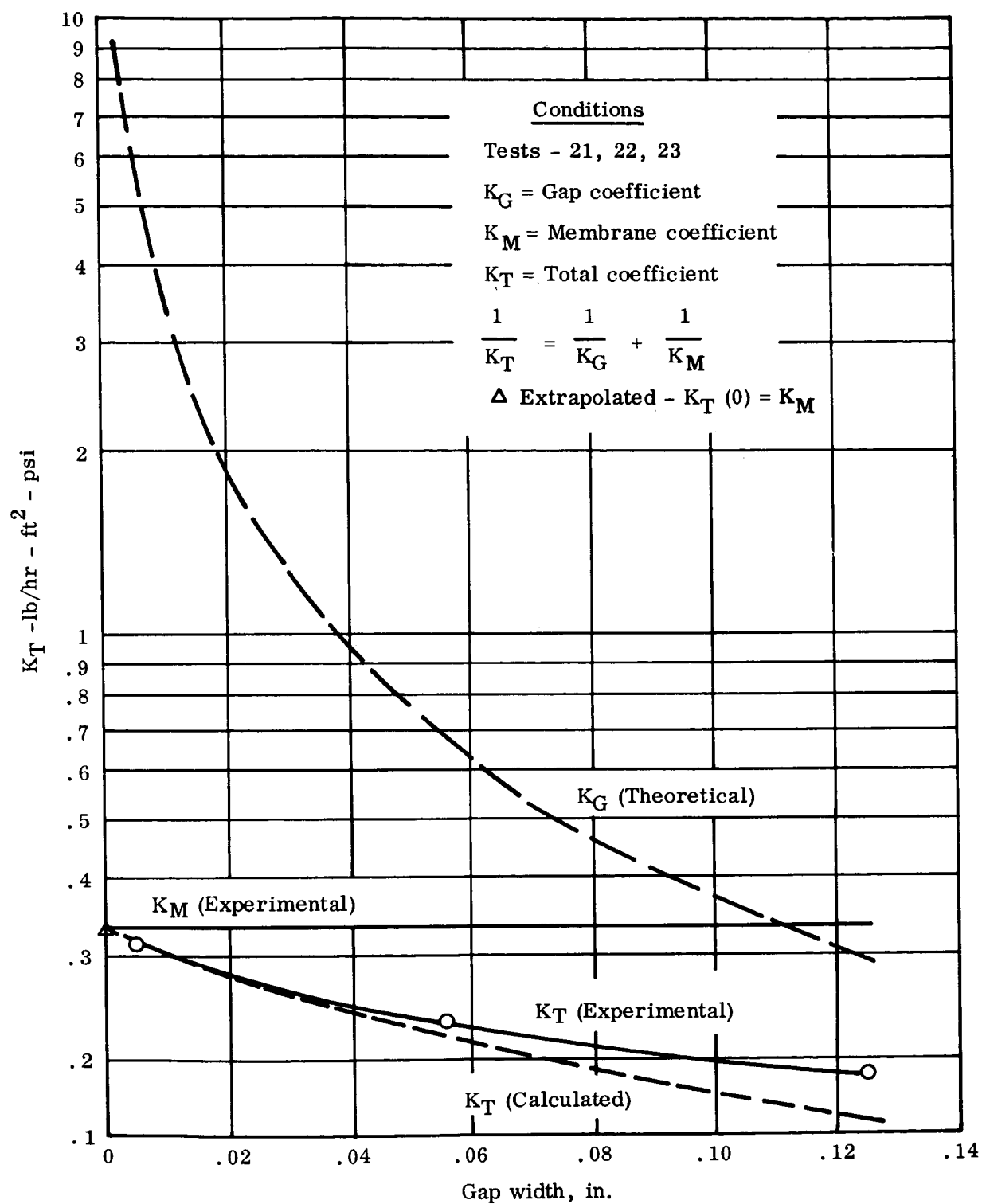


Figure 6. Diffusion Constants as a Function of Diffusion Gap Width

Vapor pressure as the driving force - tests 6-9, 17-19. - Tests 6-9 were run with constant condensing temperature and varying evaporator temperature. Tests 17-19 were run with constant evaporator temperature and varying condensing temperature. The basic data from tests 6-9 have been plotted in fig. 7. The change in rate with evaporator temperature is smooth and precise, although slightly greater than that predicted by using a constant K_t (from the lowest temperature run) in the basic relationship:

$$R = K_t \Delta P$$

The evaporator temperature in tests 17-19 was not held constant enough to provide a meaningful plot of condensing temperature vs processing rate.

The validity of vapor pressure as the driving force can be assessed from fig. 8, in which the K_t (exp) is presented as a function of total vapor pressure differential for all these runs. K_t (exp) exhibits only slight experimental scatter from a value of 0.165 lb/hr-psi, which compares well to the calculated value predicted earlier.

Effect of gap gas pressure and effect of urine recirculation rate - tests 10-16. - Tests 10-16 examined the effect of the urine recirculation rate and gap pressure on the processing rate. Test results are plotted according to the processing rate in fig. 9, and the variance of K_t with recirculation rate and gap pressure is shown in fig. 10. There are no clear trends visible in these figures and it is clear that within experimental accuracy, neither gap pressure nor urine recirculation rate had any significant effect upon the processing rate within the range of the variables studied.

TABLE III
EFFECT OF HELIUM AS INERT GAP GAS
TESTS 24-25

Test no.	Gap gas	K_m (Assumed)	K_c (Theo)	K_t (Calc)	K_t (Exp)
24	N ₂	0.323	0.304	0.157	0.192
25	He	0.323	1.085	0.248	0.278

Conditions

Urine circulation rate = 200 ml/min
 T_e , Condensing temperature = 70°F
 Diffusion gap pressure = 3 in. Hg
 Solutes concentration = 15%
 Coolant circulation rate = 500 ml/min.
 Diffusion gap width = 0.12 in.

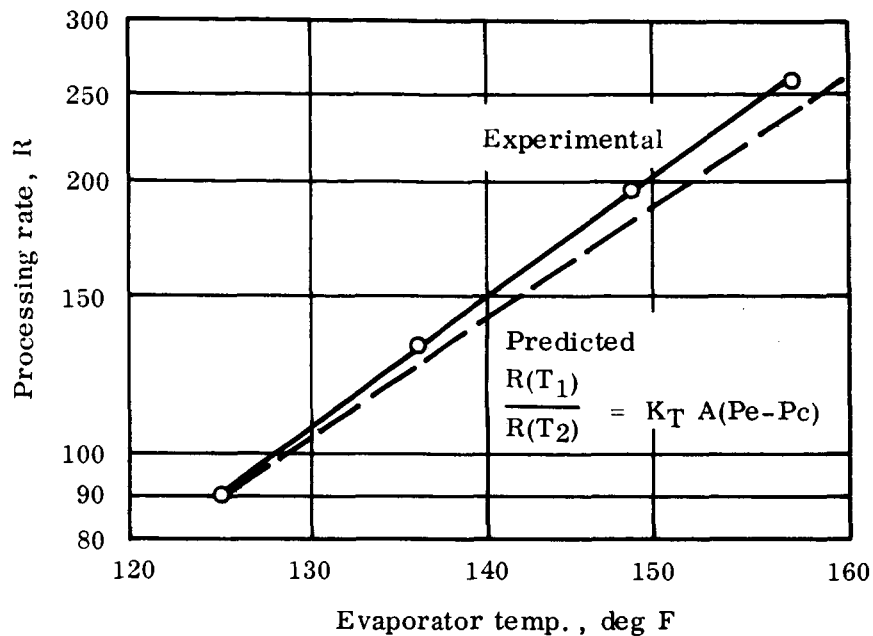


Figure 7. Processing Rate as a Function of Evaporator Temperature

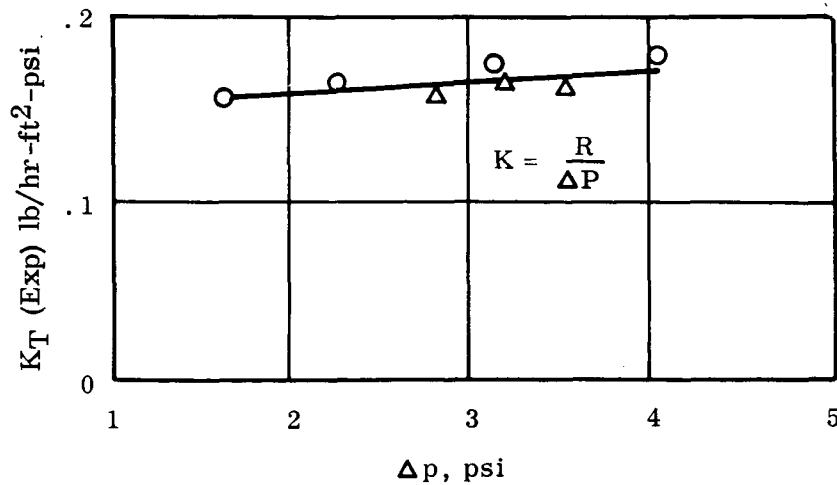


Figure 8. Overall Diffusion Constant as a Function of Vapor Pressure Differential

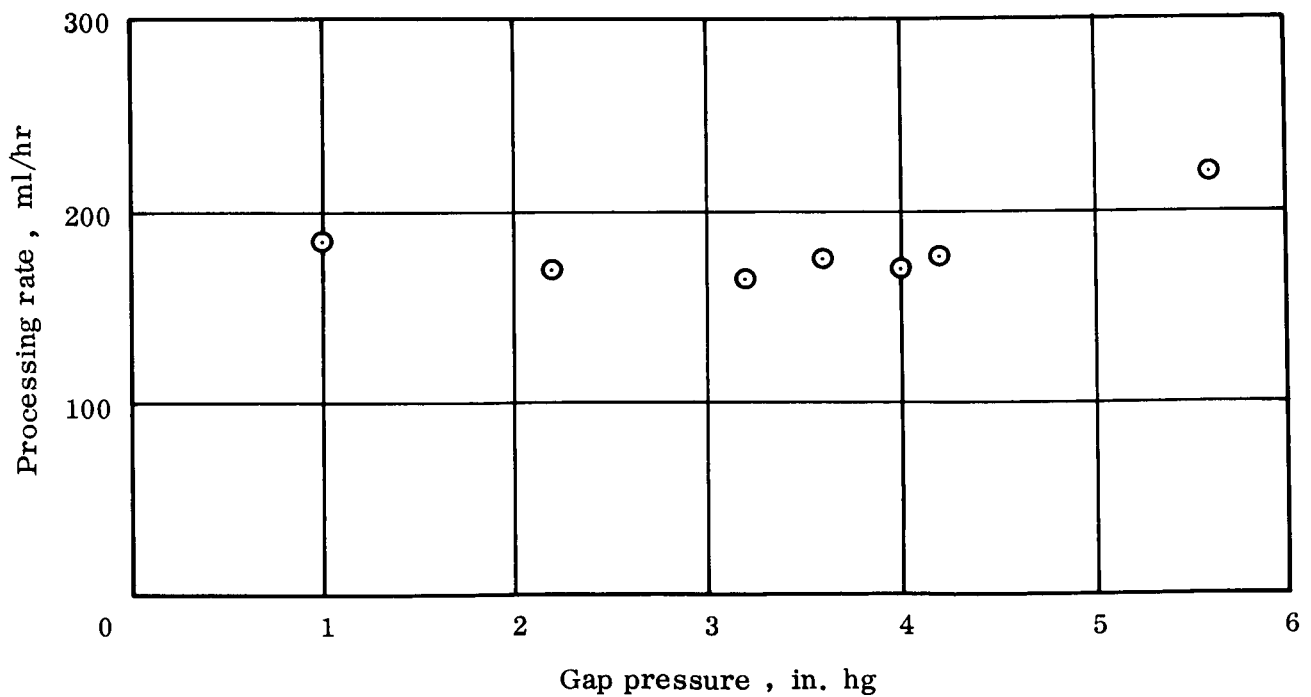
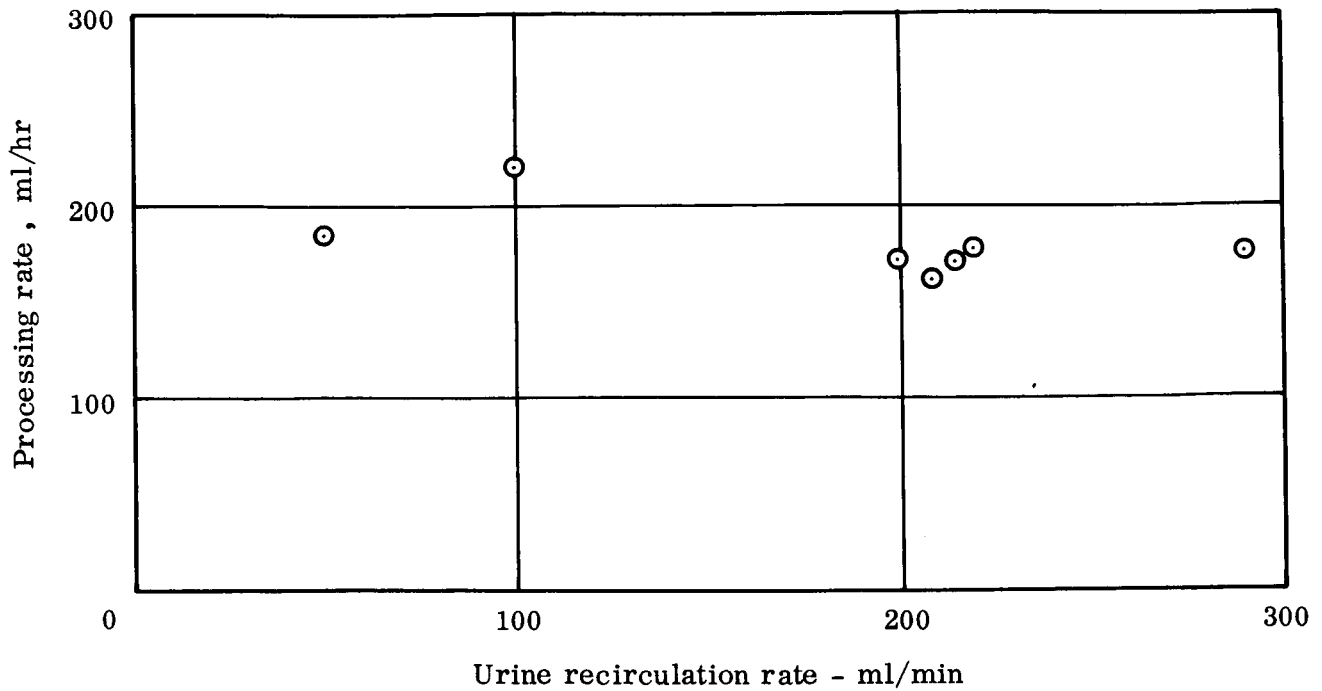


Figure 9. Processing Rate as a Function of Urine Recirculation Rate and Gap Pressure

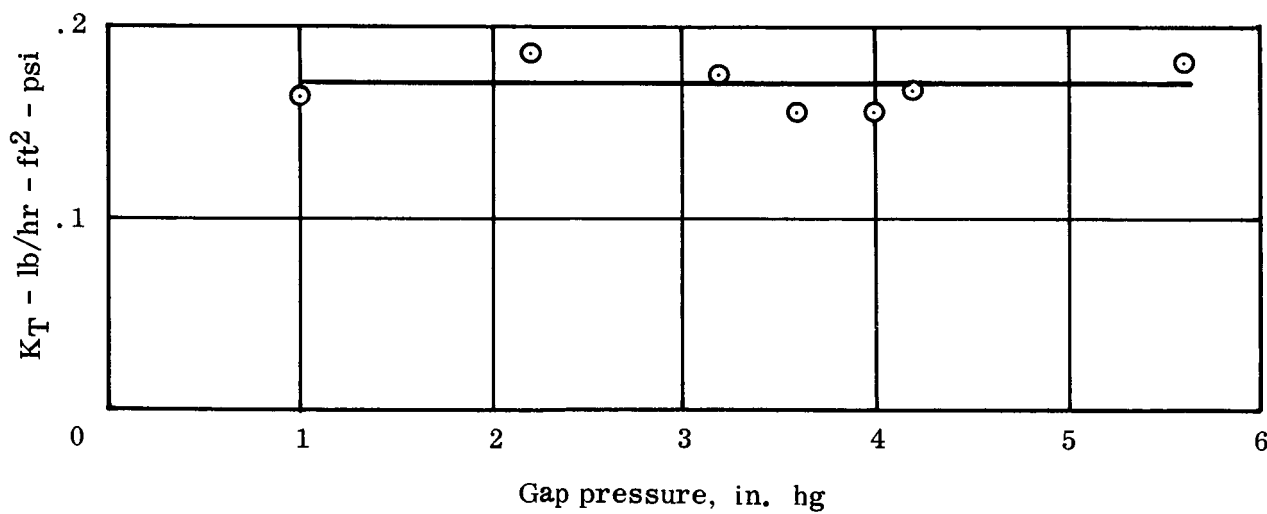
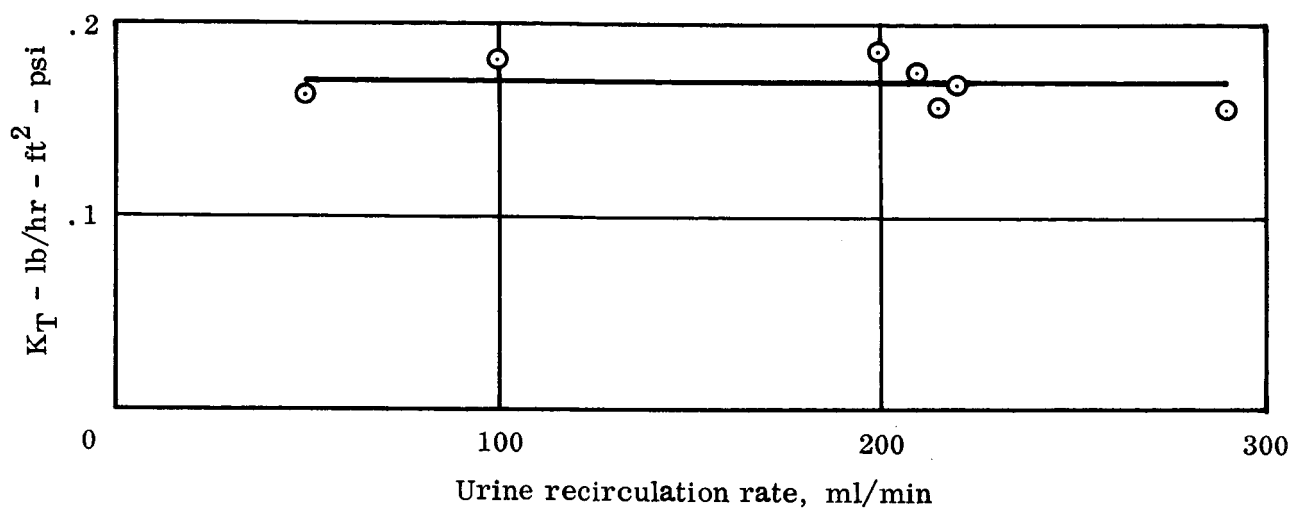


Figure 10. Overall Diffusion Constant as a Function of Urine Recirculation Rate and Gap Pressure

Conclusions

1. The important mechanisms for vapor diffusion water reclamation are:
 - a) Water vaporization at the urine-membrane interface
 - b) Diffusion of water vapor through the membrane
 - c) Diffusion of water vapor through the inert gas-pressurized vapor gap
 - d) Condensation of water vapor.
2. The controlling mechanisms at optimal conditions using membranes available or developed in this report are
 - a) Membrane diffusion
 - b) Vapor gap diffusion.

The resistance to mass transfer is evenly divided between these mechanisms when nitrogen is the inert gap gas. When helium is the gap gas, membrane diffusion controls.

3. The mass transfer of water vapor through membrane and gap follows the relationship $R = K_t A \Delta P$, where R is the diffusion rate and ΔP the difference in water vapor partial pressure between the evaporating hot urine and the condenser. K_t varies significantly only with the nature of the membrane, the gap width, and the gap gas composition. The membrane diffusion constant must be determined by experiment, but diffusion through the gap gas can be predicted from fundamental considerations.

EXPERIMENTAL EVALUATION OF SELECTED SECONDARY PARAMETERS

After the mathematical model had been formulated and verified, there remained a number of operating and configuration problems which could influence the design of a practical vapor diffusion unit.

The first section investigates the relative merits of series and parallel flow when a large number of modules are to be used together.

The second section investigates the penalties of non-recirculating urine flow.

In the third section the best possible conditions were combined to determine the maximum potable water recovery for urine.

The last section investigates the effect of batch feeding the system, which is desirable since the pretreatment will probably be batch.

Modular Flow Arrangements - Series and Parallel Urine Flow

Fig. 11 shows the alternate plumbing arrangements for three modules connected for series and parallel urine flow.

A brief consideration of the two flow methods indicates that series flow will involve less urine recirculation because the pressure drop will be about 36 times as great. In the actual case the total outlet flows were controlled to 12 ml/min for series flow and 200 ml/min for parallel flow. Since the water processing rate was relatively high, a circulation rate of 12 ml/min indicated an extremely high concentration of solids in the outlet urine. Without the benefit of rapid recirculation, this high concentration could permit the establishment of significant concentration gradients near the membrane, encouraging solids precipitation. Such apparently was the case, since the processing rate for the series flow arrangement deteriorated rapidly with processing time (fig. 12).

Non-Recirculating Urine Flow

The work in the previous section indicates that highly concentrating the urine in one pass is deleterious to membrane life. A single test was run in which the concentration was extreme: the urine outlet flow was only 1.5 ml/min. Table IV describes this test. Only one-third of the expected solids were found in the urine effluent, supporting the conclusion that precipitation was occurring in the module due to locally high internal concentrations. The membrane failed after only 10 hr, supporting the contention that solids precipitation in or near the membrane is not permissible. Urine flow over 100 ml/min prevents this problem.

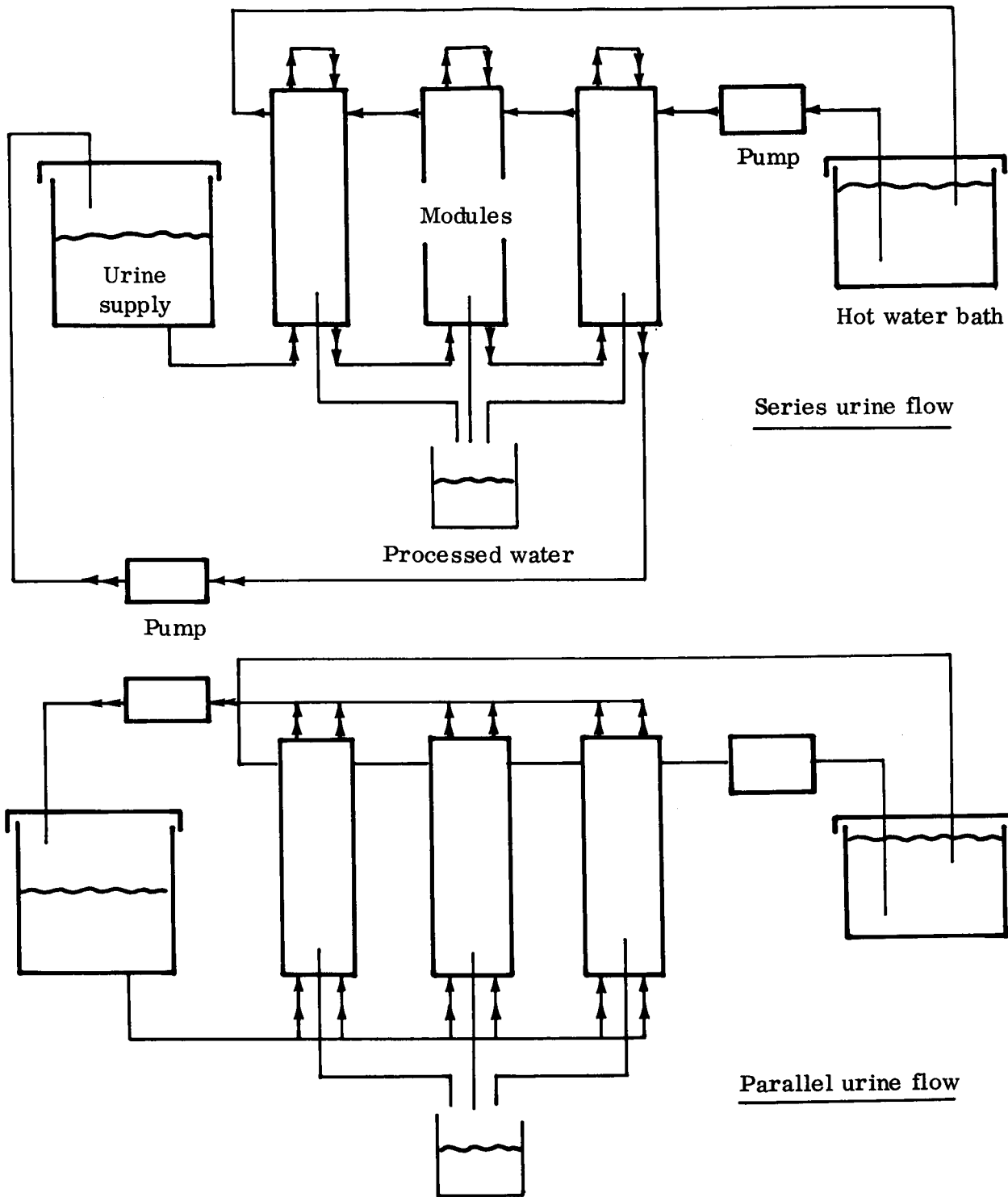


Figure 11. System Arrangement for Series and Parallel Flow - Schematic

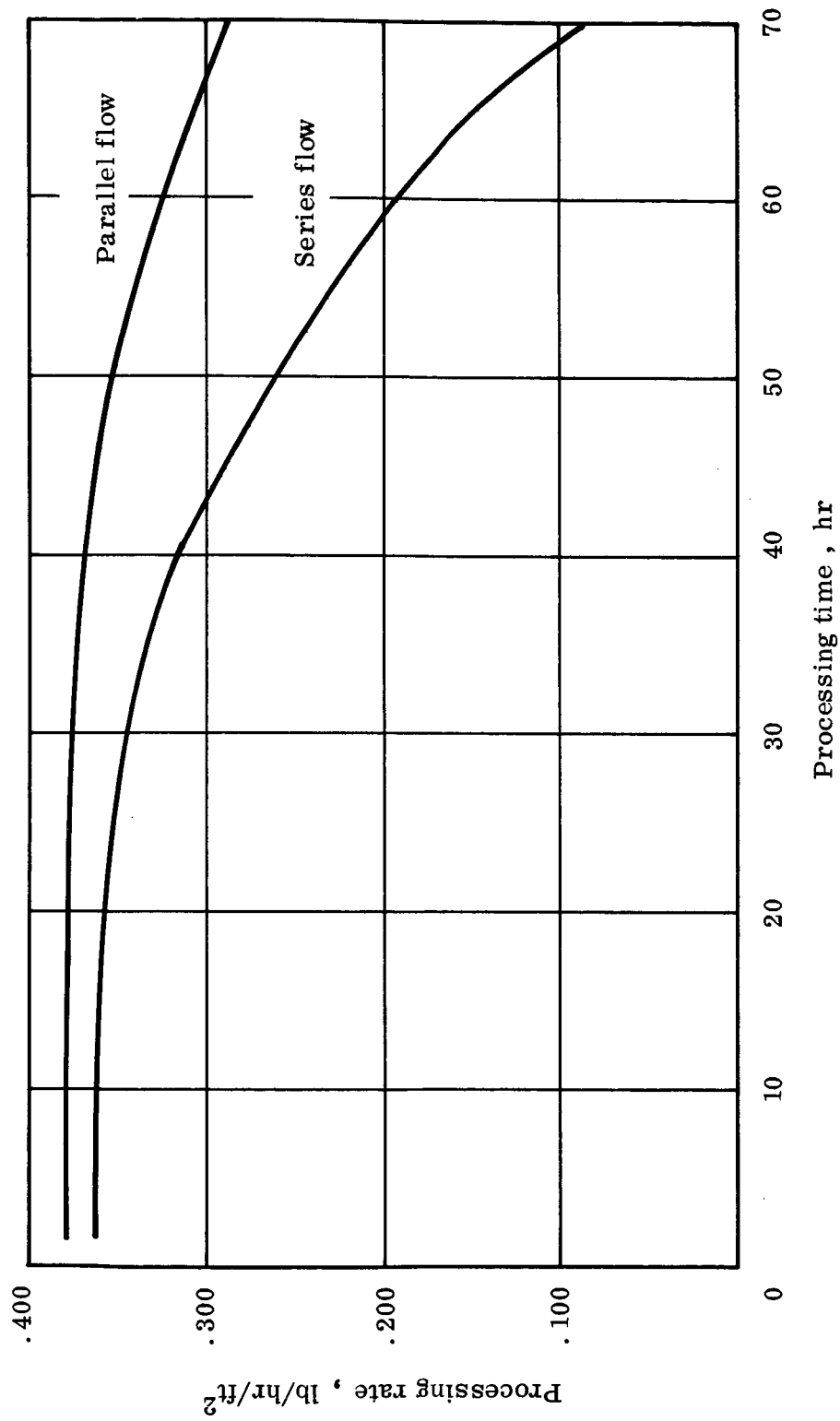


Figure 12. Processing Rate as a Function of Time for Parallel and Series Urine Flow Through the Modules with Continuous Urine Feed

TABLE IV

NON-RECIRCULATING URINE TEST

<u>Average urine outlet flow rate</u>	<u>Average water processing rate</u>	<u>Water recovery % of possible</u>	<u>Membrane life</u>
87 ml/hr	435 ml/hr	84%	10 hr

Maximum Recovery

The 84% recovery in the previously discussed test can be considerably bettered by recirculating the brine flow rapidly to prevent local concentration gradients from developing within the module. Fig. 13 shows the processing characteristics of the system using a urine recirculation rate of 200 ml/min on a single 10 lb batch of urine. Water recovery was 98% when the test was terminated. At this point the solids in the brine were 66% by weight.

The dotted line shows the drop in rate to be expected as a result of decreasing partial pressure of water in the increasingly concentrated solution. The further drop-off of the actual curve can be attributed to membrane fouling.

Batch vs Continuous Feed

Continuous feed, as used in this work, was intended to represent a possible urination pattern. Small quantities of fresh pretreated urine were periodically added to the circulating volume, maintaining a realistic solids concentration level for the duration of the test.

Batch feed was intended to represent storage of urine during the processing of a previous batch until the solids in the brine reached about 50%. The parameters of the system were such that a batch feeding was made every 24 hr, a convenient time period for manual cycling of a spacecraft system.

Fig. 14 shows the effect of this feeding method on the processing rate. After the second batch was added, the processing rate recovered to that appropriate to the solids content of the system. These curves may be compared to those of fig. 12, generated with continuous feed.

Either batch or continuous feed could be used in an actual application. Each can maintain reasonable processing rates, and either can do as well in percent recovery of water.

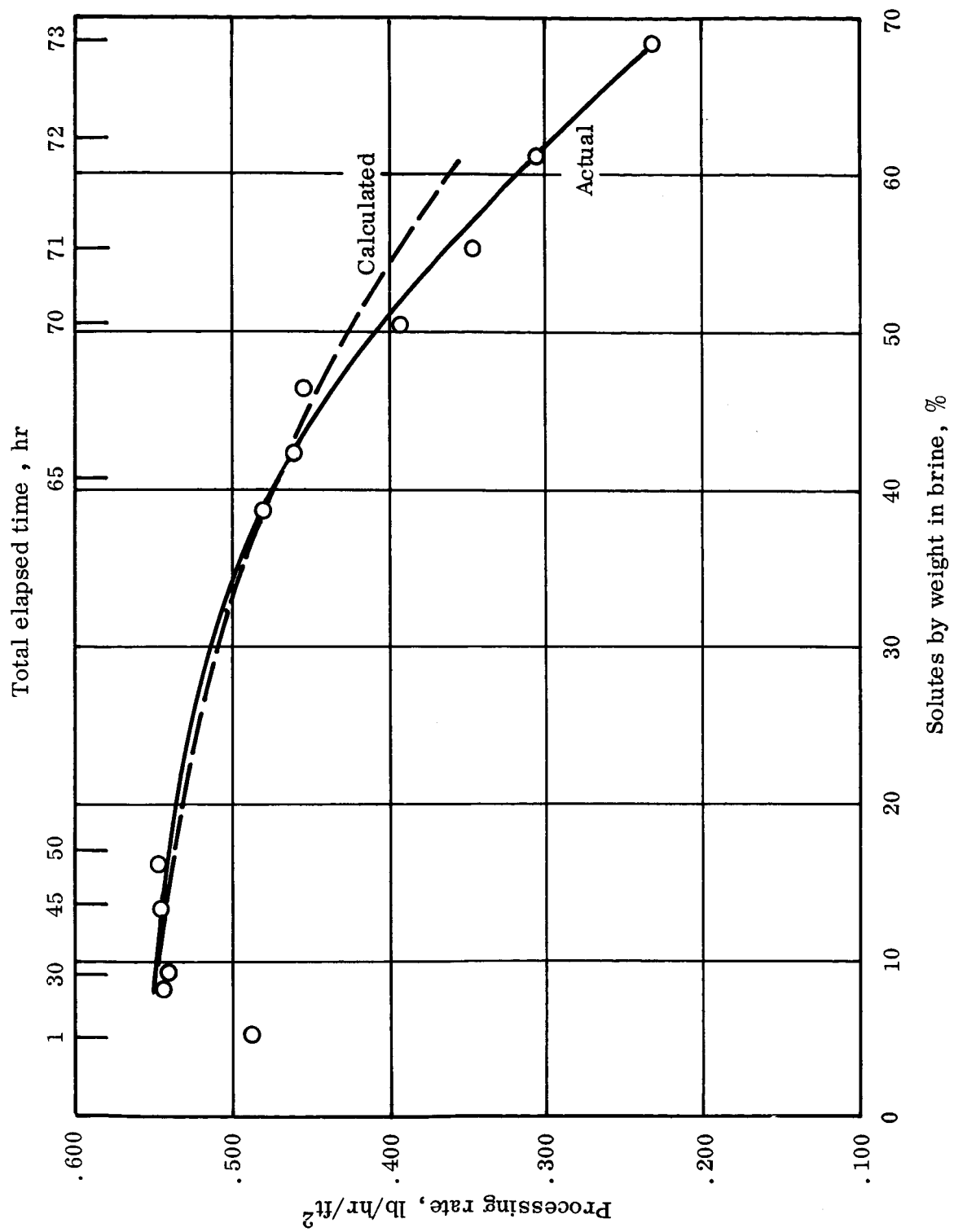


Figure 13. Processing Rate as a Function of Urine Solids Concentration

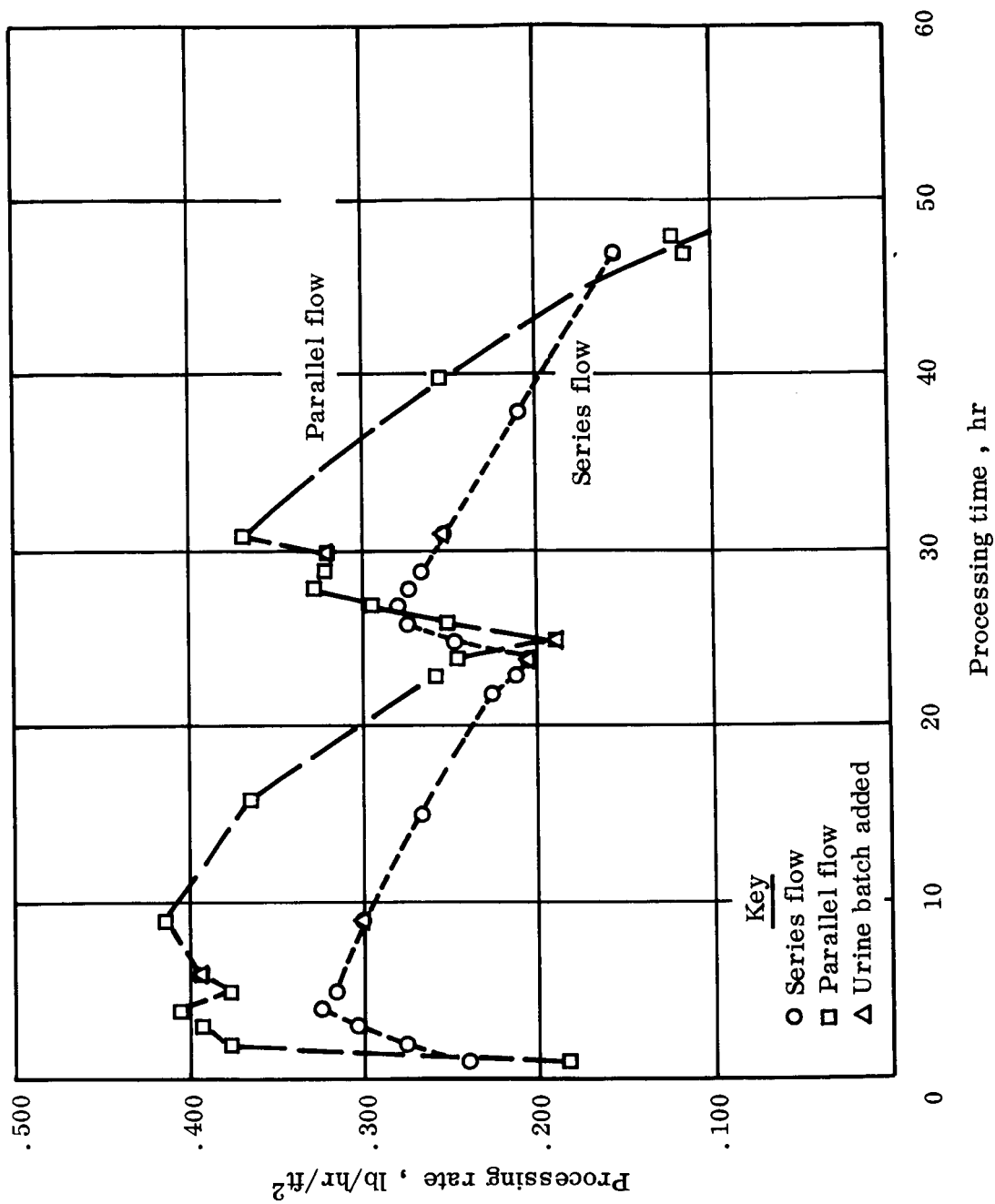


Figure 14. Processing Rate as a Function of Time
for Urine Batch Feed

The average processing rate of the batch system will be only about 75% of the continuous rate due to the periodically high solids concentrations characteristic of this method of operation

Conclusions

1. Hot urine must be recirculated to prevent precipitation of urine salts in or near the membrane causing premature membrane failure. In the experimental configuration tested, a recirculation rate of 50 ml/min was adequate.
2. As much as 98% of available water could be recovered from the urine, which left a solution of about 50% urine salts (by weight) plus precipitated salts crystals which did not interfere with membrane operation.
3. Feed can be continuous or intermittent without adverse effects on performance beyond that due to changes in partial pressure of water vapor in the urine.

MICROBIOLOGICAL STUDY

Objectives

The objectives of this study were:

1. To determine the inherent microbiological characteristics of the vapor diffusion water reclamation system.
2. To determine the microbiological quality of water produced by the vapor diffusion water reclamation system.

These objectives were achieved by subjecting the following specimens to the bacterial analysis:

- a) Urine - as collected and after process pretreatment
- b) Activated charcoal - as received and after sterilization
- c) Processed water from sterile system - before and after charcoal post treatment
- d) Processed water from contaminated system - before and after charcoal post treatment
- e) Activated charcoal - after exposure in contaminated system.

Tests results are measured in two ways, bacteria count (or the number of bacteria per unit measure) and the type of bacteria present. Low bacteria count and freedom from pathogenic species are the accepted standards for microbiological safety.

Rationale of Inherent Microbiological Safety in the Vapor Diffusion System

The water produced by any reclamation system must be chemically and microbiologically safe, as well as organoleptically acceptable. The microbial content of the water must be low in number and free of all pathogenic species and their toxic by-products. The membrane vapor diffusion system inherently produces a microbiologically safe, potable water by the sequential application of various microbial control procedures including:

1. Chemical treatment
2. Pasteurization
3. Distillation
4. Filtration
5. Sterilization

Chemical Treatment. - Chromic acid solution, consisting of chromium trioxide, water and sulfuric acid, is primarily used for the fixation of urea and uric acid components of urine to prevent their chemical and/or microbiological degradation to ammonia. A secondary function of the pre-treatment acid is the inhibition of microbial growth. Chromic acid is a strong oxidizing agent and by virtue of this property and effectively controls the number of micro-organisms contaminating urine or wash water. In addition to the oxidizing properties, chromic acid also increases hydrogen-ion concentrations to produce acidic conditions inhibitive to bacterial growth. The acid solution contains chromium ions which also may be mildly bacteriostatic.

Pasteurization. - An important phase of the membrane vapor diffusion process is the heating of the process liquids to 140°F. Considering the liquid recirculation which occurs over an extended period of time and the temperature used in the process, this phase is comparable to a pasteurization procedure. Industrial pasteurization utilizes temperatures of 140 and 160°F for 30 min and 15 sec, respectively, to effectively reduce microbial numbers to safe levels, especially non-spore forming pathogens.

Distillation. - The heating of the liquids being processed to 140°F slowly converts the liquid to the vapor phase during passage through the barrier membrane of the vapor diffusion process. In zero gravity in an ordinary distillation process, microbial cell release would be facilitated at the liquid-gas interface. Since the liquids intimately contact only the membrane, this interface is not present and the cells are contained in the liquid.

Filtration. - The membranes used in the vapor diffusion process possess a microporous or gel structure which allows the passage of only molecular-sized materials. This molecular-sized porosity of the membranes will effectively retard the passage of most microbial cells, even to the smallest bacteria (0.3 micron), but would not necessarily stop virus particles.

Sterilization. - The antimicrobial features of the membrane diffusion process discussed above will control microbial growth in the input side of the membrane. However, the production of germ-free water will depend on the sterility of the components of the system on the output side of the membrane.

The inherently aseptic nature of the membrane vapor diffusion system, combined with the simple initial sterilization of the system components, will assure the maintenance of a microbiologically safe water supply.

Test Procedures

The procedures used in the conduct of these tests were as follows. Urine was collected from male volunteer donors and mixed to obtain a sufficient quantity for processing through a single module membrane vapor diffusion apparatus. A portion of the mixed urine was sampled for bacterial count. The remaining urine was treated with the usual pretreatment, a solution of chromic acid. An aliquot of the treated urine was sampled for bacterial count. Plate counts on the treated and untreated urine were performed according to standard laboratory procedures.

A sample of activated charcoal, as received from the manufacturer, was tested for indigenous bacterial populations. Eleven (11) grams of the charcoal were introduced into 99 grams of sterile distilled water and thoroughly agitated. Aliquots of the water were removed and plated in Trypticase Soy Agar. The plates were incubated for 48 hr at 90-95°F. Sterilized charcoal was similarly tested.

One complete processing module, processed water collection lines, and a canister with activated charcoal were sterilized with dry heat at 350°F for two hr. The materials were removed from the oven and allowed to cool. Non-sterile membranes were mounted in the modules, the apparatus was assembled and the vapor diffusion process started.

Ten ml samples of the processed water were collected in sterile test tubes before and after the sterile activated charcoal filter after 24 and 72 hr intervals. The samples were filtered through Millipore bacteriological membranes, plated on Total Count Media and incubated at 90 - 95°F for 24 - 48 hr.

One side of the processing module was then deliberately contaminated by introducing ten ml of a heavy bacterial suspension into the diffusion gap through the gas pressurization port and the processing continued. Ten ml samples of the processed water were collected and tested as above for total count after four, twenty-four, and forty-eight hours of additional processing.

Processing was then discontinued and the apparatus disassembled. The charcoal was enclosed in a plastic bag and stored at room temperature for five days and tested once more for total bacteria count.

Results

The results of the bacterial analyses are tabulated below. Inspection of these analyses shows both the processed water and the vapor diffusion reclamation system contain zero detectable bacteria. Average bacteria count in municipal water systems ranges in the low hundreds per ml. Results also indicate that the rationale of destroying bacteria in the system as presented above is valid. Contaminating the system with a heavy bacterial suspension was followed by a drastic reduction in bacteria count

during the subsequent 24 hr of operation. A small increase in the next 24 hr was within acceptable limits. A relatively high bacteria count downstream of the charcoal after 48 hr points to a potential colonizing area for bacteria in the charcoal canister.

The results of the experiments conducted with pretreated urine showed a reduction of bacteria from 2.7 million to 3.2 thousand after a short contact time with the chromic acid pretreatment solution. The experiment further validates the rationale for inhibiting bacterial growth as presented above.

<u>Sample (uninoculated)</u>	<u>Bacteria/ml</u>
Composited urine	2,700,000
Treated urine	3,240
Processed water 24 hr	
Before charcoal	0*
After charcoal	0*
Processed water 72 hr	
Before charcoal	0*
After charcoal	0*
<u>Sample</u>	<u>Bacteria/gram (dry)</u>
Activated charcoal, as received	170
Activated charcoal, sterilized	0*
<u>Sample (inoculated test)</u>	<u>Bacteria/ml</u>
Processed water 0 hr (uninoculated)	
Before charcoal	0*
After charcoal	0*
Processed water 4 hr	
Before charcoal	7,000
After charcoal	7,000
Processed water 24 hr	
Before charcoal	20
After charcoal	20
Processed water 48 hr	
Before charcoal	170
After charcoal	1,000
Charcoal (inoculated, 7 day contact)	35,000/gram (wet)
*No bacteria detected by direct count of 10 ml/sample.	

Conclusions

Based on the results of the bacterial analysis, the following can be concluded:

1. The processed water produced by the vapor diffusion reclamation process is bacteriologically pure.
2. The vapor diffusion system, when operating, contains several inherent control operations that destroy or inhibit bacterial growth. The net result is the production of microbiologically safe water.
3. The pretreatment of urine with chromic acid solution is an effective method of controlling bacterial growth.

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MEMBRANE STUDY

Objectives

A membrane study was made to identify and select candidates to replace the cellophane membrane presently in use. To be used effectively in a vapor diffusion water reclamation system, a membrane must exhibit the following characteristics:

1. Provide high performance permeation of water vapor while preventing the passage of impurities into the product water stream.
2. Maintain structural integrity during long exposures to chemically-treated urine.
3. Extend performance duration to eliminate the need for frequent replacement.
4. Promote simplified replacement techniques by reason of handling and/or fabrication characteristics.

The cellophane membranes tested to date have a short useful life as measured in pounds of water processed per square foot of membrane surface. In addition, fabrication is limited to mechanical sealing methods. Many other commercially available membranes can be bonded or heat sealed into modules or cartridges for easy handling and replacement. Since these commercial membranes are markedly superior to cellophane in handling and fabrication characteristics, the membrane study was directed towards investigating the permeability, structural integrity, and water processing performance of the candidate materials.

Study Approach

A materials study of selectively permeable membranes could be approached by either theoretical or empirical methods. The theoretical approach could be employed by attempting to isolate the physical properties of the candidate materials, but this has been found to be ineffective because of the lack of information about specific material properties and the failure of analytical techniques to successfully correlate these properties with performance data. For these reasons, an empirical approach was selected.

Experimental Objectives

The purpose of the membrane investigation was to select, based on test results, a membrane (or membranes) that would possess all the favorable characteristics of

cellophane, be easily fabricated, and have a greater structural integrity and longer life than cellophane.

Membrane life, expressed in pounds of water processed per square foot, is an inherent characteristic of the material and is not altered significantly by variations of operating parameters. The structural integrity of a material is simply its ability to withstand the exposure to the combination of chemicals, heat, and stresses encountered in the system. Ease of handling and fabrication is a subjective measure and may be noted only on a comparative basis.

Description of Experiments

Materials for testing were procured from known manufacturers and suppliers of membranes who responded to Hamilton Standard solicitations based on a brief description of desired properties and characteristics. A total of 37 material samples were received, of which all but two (sample numbers 31 and 37) are in regular production. Of these, four (sample numbers 33 to 36) required special treatment prior to use and were rejected without test. Six additional membranes (sample numbers 38 to 43) were produced in the Hamilton Standard Materials Laboratory from various raw materials. A complete list of the sample materials and their manufacturers is presented in table V.

All materials were initially tested for permeability and compatibility with pre-treated urine. These tests were conducted in either a system evaporator or a filter holder evaporator, depending on sample size. Tests of cellophane membrane were made in each evaporator to provide baseline data for comparison. The test set-ups are shown schematically in fig. 15. Data from these tests is summarized in table V. Reported permeabilities are corrected to a 140°F evaporating temperature. An additional correction, based on the extrapolation of baseline data, was made for the filter holder evaporator tests (sample numbers 28 to 32).

As a result of the first series of tests, two candidate membranes and a cellophane membrane were installed in the vapor diffusion water reclamation system and tested to failure. These tests established membrane life and structural integrity. Fabrication and handling characteristics of these materials were observed and compared to the baseline standards during test system set-up. The results of these tests are shown in figs. 16, 17, and 18.

Results

Of the forty-three various types of membranes tested, Nalco's polyvinylchloride based gel-structured material (sample number 1) proved to be the most attractive. This material maintained its structural integrity throughout 1296 hr of constant exposure to pretreated urine and during that time produced potable water at an average rate

TABLE V
MEMBRANE INVESTIGATION DATA FOR URINE COMPATIBILITY
AND WATER VAPOR PERMEABILITY

Sample No.	Material	MFR - type	Thickness mils	Permeation ml water	Time, hr.	Urine temp. °F	Correction factor	Permeability ml/hr in. ²	Rejection reason
--	Cellophane	DuPont PD 128	1.6	215	3.50	129	1.41	1.52	
1	Polyvinylchloride	Nalco D30	4.0	345	4.00	139	1.03	1.56	
2	Cellulose acetate	Desalination MF10	3.0	345	5.00	125	1.59	1.92	Brittle, easily torn
3	Glass cloth- teflon	Pall TV20A40	4.5	260	3.00	137	1.10	1.67	Gas permeable
4	Parchment	Brosite	--	305	4.00	124	1.67	2.23	Breaks down when wet
5	Cellulose nitrate	S & S B-11	5.5	260	3.25	128	1.45	2.03	Easily torn
6		Pall TX40H75	--	175	2.45	141	0.97	1.22	Gas permeable
7	Cellulose acetate	Monsanto	7.0	60	23.00	133	1.25	0.056	Low permeability
8	Cellulose tri- acetate	Eastman TA404	1.5	75	3.00	147	0.83	0.36	Not fabricable
9	Cel. ace. butyrate	Eastman K'pak II	1.6	140	18.00	137	1.10	0.15	Low permeability
10	Cellulose acetate	Cellanese P904	12.0	65	20.00	146	0.85	0.048	Low permeability
11	Polyvinylfluoride	DuPont 200SG40TR	2.0	0	17.00	142	0.95	0.000	Low permeability
12	Polystyrene	Monsanto	1.0	15	17.00	142	0.95	0.015	Low permeability
13	acrylonitrile	Enjay	--	7	4.00	173	0.044	0.013	Low permeability
14	Polypropylene	Hercules N402/23	5.0	20	4.00	173	0.044	0.039	Low permeability
15	Impact styrene	Monsanto	1.0	35	16.50	144	0.089	0.033	Low permeability
16	Polyurethane	Monsanto	18.0	5	16.50	144	0.089	0.005	Low permeability
17		Pall T10GNG	--	35	18.00	141	0.97	0.033	Gas permeable
18	Cellulose nitrate	S & S MC-4	--	425	17.50	138	1.06	0.45	Film on filter
19	Glass cloth- teflon	Pall TV20A60	--	65	3.50	136	1.14	0.37	paper, easily torn Gas permeable
20	Polyurethane	Rowland	5.0	80	22.00	147	0.83	0.053	Low permeability
21	Polyvinylfluoride	DuPont 200BG30WH	2.0	10	22.00	149	0.79	0.006	Low permeability
22	Glass - teflon	Pall FTX 10A70		85	1.50	124	1.67	1.66	Gas permeable
23	Glass - teflon	Pall TX 60130		255	17.50	124	1.67	0.43	Gas permeable
24	Glass - epoxy	Pall EX 10A65		28	9.00	124	1.67	0.91	Gas permeable
25	Cellulose acetate	Millipore EG		0	6.00	142	0.95	0.00	Low permeability

TABLE V (Concluded)
MEMBRANE INVESTIGATION DATA FOR URINE COMPATIBILITY
AND WATER VAPOR PERMEABILITY

Sample No.	Material	MFR - type	Thickness mls	Permeation ml water	Time, hr.	Urine temp. °F	Correction factor	Permeability ml/hr in. ²	Rejection reason
26	Cellulose acetate	Millipore EH		0	6.00	142	0.95	0.00	Low permeability
27	Cellulose acetate	S & S B6-A	5.5	275	3.00	142	0.95	1.53	Brittle, easily torn
28	Anion	AMF A-104-EC	6.0	2.5	7.00	140*	1.50	0.60	Permeable to solids
29	Cation	AMF C-103-FE	8.0	1	9.00	140*	1.50	0.19	Low permeability
30	Polyvinylchloride	S & S PVC-6	5.5	8.5	10.00	140*	1.50	1.43	Gas permeable
31	Polyethylene vinylacetate	Monsanto	7.0	0.0	6.00	138*	1.59	0.00	Low permeability
32	Nitrocellulose	Millipore HA		3.0	2.50	157*	0.94	1.29	Easily torn
--	Cellophane	DuPont PD128	1.6	4.5	5.00	140*	1.50	1.52	
33	Polystyrene sulfonic acid	Nalco Nalfilm 1	--	--	--	--	--	--	Wet membrane
34	Polyvinylbenzyl trimethyl ammonium hydroxide	Nalco Nalfilm	--	--	--	--	--	--	Wet membrane
35	Cellulose acetate	S & S B17	--	--	--	--	--	--	Wet membrane
36	Cellulose derivatives	S & S 02	--	--	--	--	--	--	Wet membrane
37	Silicone rubber	G. E.	--	--	--	--	--	--	Permeable to solids
38	Polyvinyl alcohol	DuPont	--	1.0	12.00	140*	1.50	0.14	Low permeability
39	Polyvinyl butyrate	Union Carbide	--	1.0	18.00	140*	1.50	0.094	Low permeability
40	Polyvinyl acetate	Air Reduction	--	1.5	7.00	142*	1.40	0.34	Breaks down when wet
41	Polyvinyl acetate & nylon	Belding Corticelli	--	1.0	14.00	140*	1.50	0.12	Low permeability
42	Copolymer polyvinylchlorine & polyvinyl acetate	Air Reduction	--	0.5	12.00	140*	1.50	0.07	Low permeability
43	Polyvinyl acetate & copolymer-vinyl chlorine with vinylidene chloride	Firestone	--	0.0	6.00	142*	1.40	0.0	Low permeability

* - Water bath temperature.

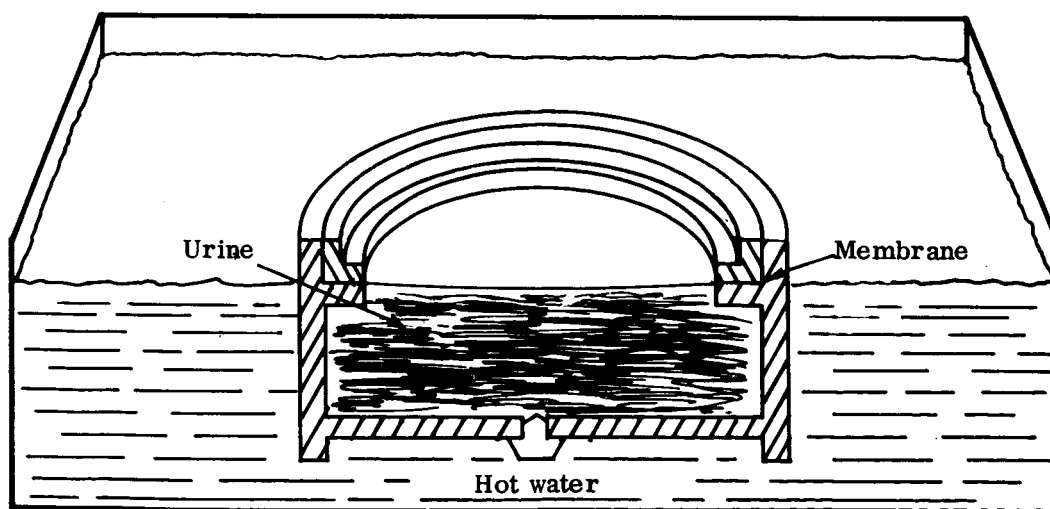
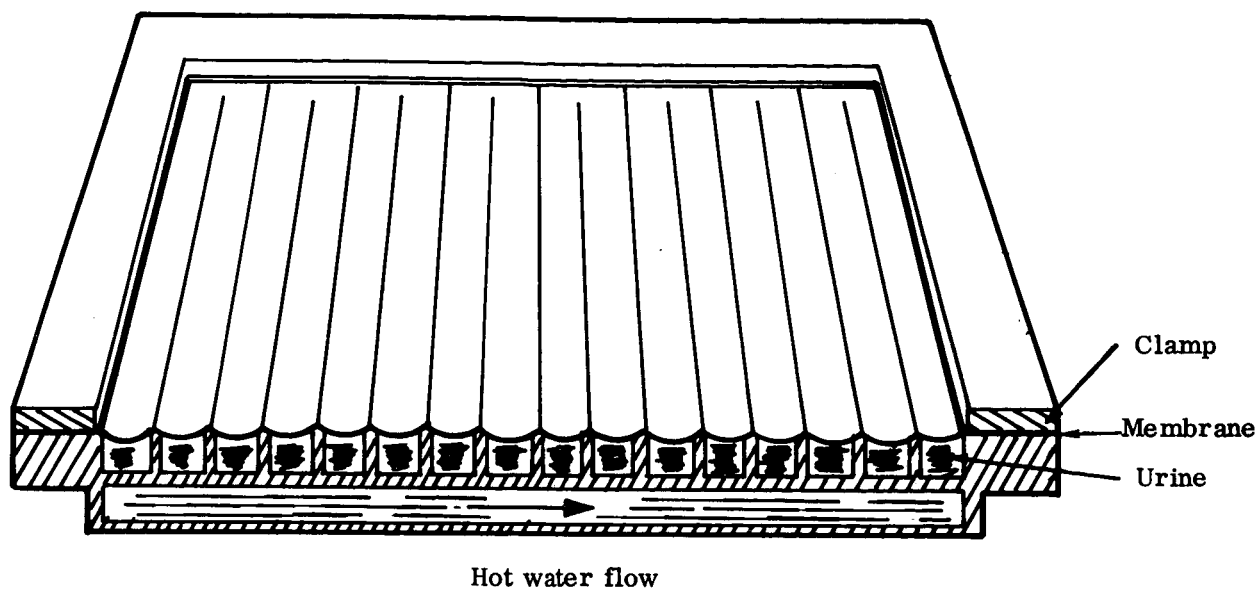


Figure 15. Membrane Test Set-Ups - Schematic

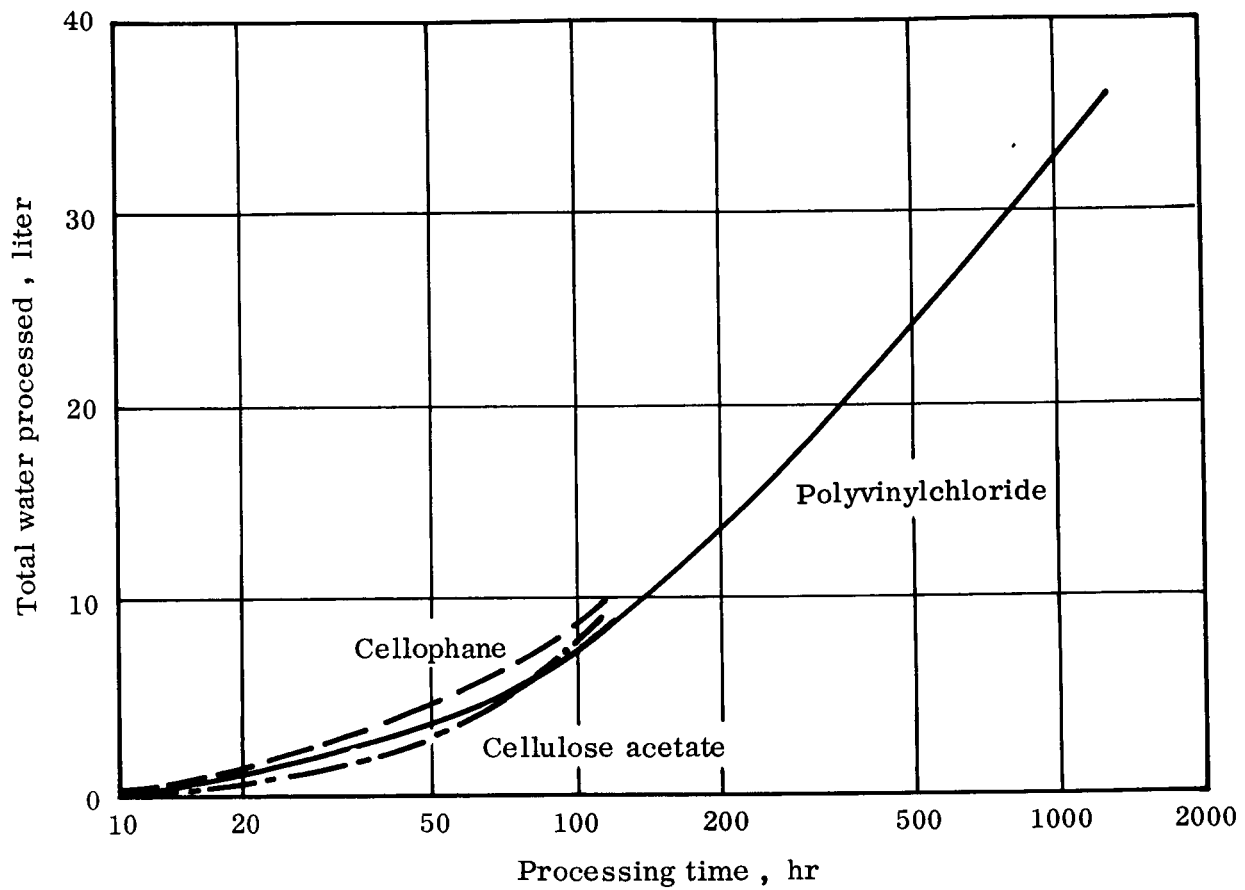


Figure 16. Amount of Water Processed as a Function of Time for the Three Best Membranes

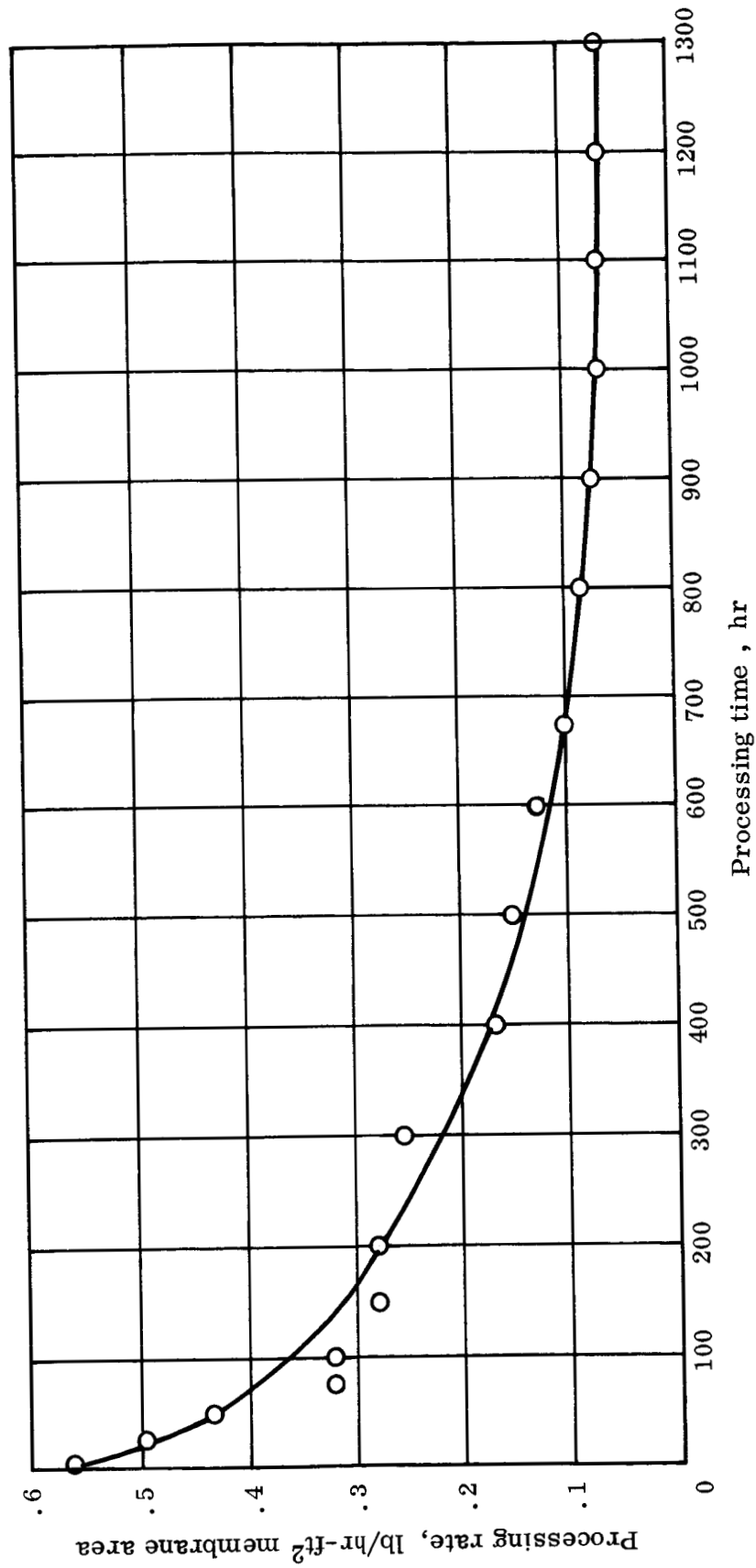


Figure 17. PVC Membrane Processing Rate as a Function of Exposure Time

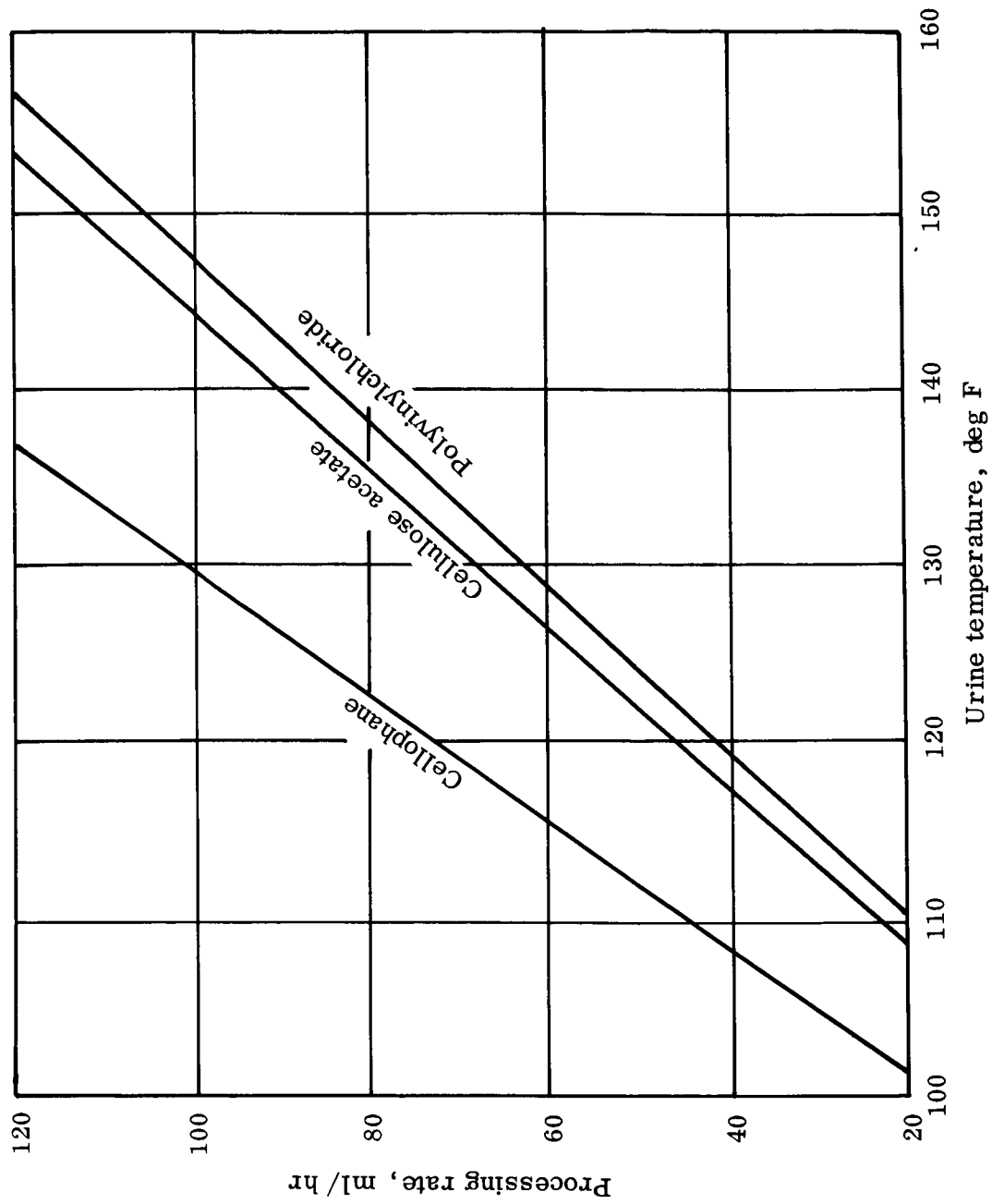


Figure 18. Processing Rate as a Function of Urine Temperature for the Three Best Membranes

of 0.155 lb/hr ft². It is bondable and heat sealable and has a useful life of over 200 lb/ft².

The initial test of the PVC material in a system module was terminated by the deformation of the membrane into the urine flow passages due to the effects of temperature and pressure in setting up stresses between the supporting webs. Since this problem may be eliminated by the fabrication of the membrane into a fully supported cartridge, another PVC sample was tested by arranging the existing system, as shown in fig. 19, with a constant, minimum differential pressure across the membrane. In this test, 36.2 liters of water were produced by one membrane over a period of 1,296 hr. The test was terminated upon the development of a pinhole leak through an inclusion in the membrane. At the conclusion of the test, a heavy solids build-up was observed on the surface of the membrane which was in contact with the circulating urine. A plot of amount processed versus time for the cellulose acetate, polyvinylchloride and cellophane is shown in fig. 16. A plot of processing rate versus urine temperature, drawn from the data points of fig. 16, is shown in fig. 18.

The only other membrane among those tested that compared favorably with cellophane was Schleicher and Schuell's microporous cellulose acetate material (sample number 27). Since this material is not heat sealable, is difficult to bond, and is brittle and easily torn during handling, it is less attractive than the PVC.

Although many candidate membranes exhibited characteristics that equalled or exceeded those of cellophane, they were rejected for other reasons. For example, of the ten samples that displayed permeabilities near that of cellophane (sample numbers 1-6, 22, 27, 30 and 32), four were rejected because of fragility (sample numbers 2, 4, 5 and 32). The gas permeability observed in the three Pall Corporation samples (numbers 3, 6 and 22) became higher in the test module, creating a steady stream of bubbles in the urine lines and preventing an adequate flow of urine under the membrane. This same phenomenon, while not witnessed in the preliminary test of the Schleicher and Schuell PVC-6 (sample number 30), also caused the rejection of this material.

Schleicher and Schuell cellulose acetate (number 27) produced 9.2 liters of acceptable water in 116 hr. This rate was slightly lower but more constant over the range of solids concentration than cellophane until developing a pinhole leak at a stress point. Of the six membranes produced in the Hamilton Standard Materials Laboratory, five exhibited low permeation rates and the sixth was incompatible with pretreated urine.

Conclusions

A comparison of the useful membrane lives of cellophane (55 lb H₂O/ft²) and Nalco PVC (250 lb H₂O/ft²) shows that a significant gain in membrane life was achieved during this investigation. The Nalco PVC met all but one of the study objectives, that of structural integrity. (This material was of marginal quality because the sole manufacturer made no provisions for quality control in the amounts supplied. Future tests of PVC should be made with material manufactured under stringent quality control.)

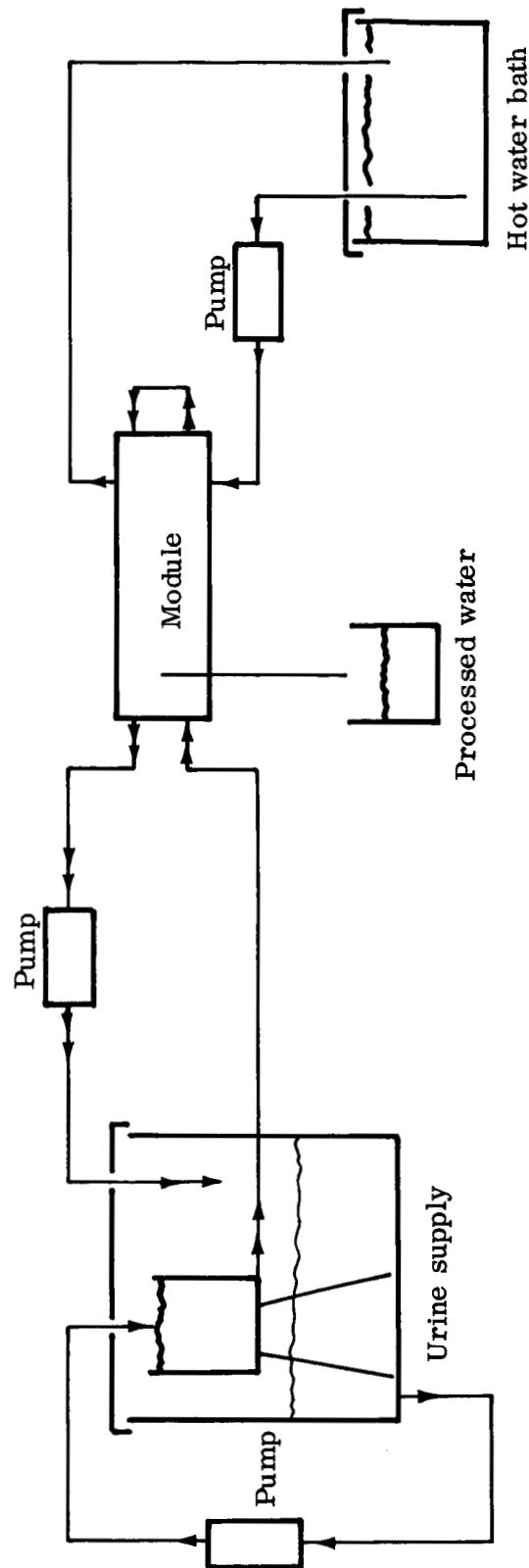


Figure 19. PVC Constant Pressure Differential Test Set-Up - Schematic

The Schleicher and Schuell cellulose acetate membrane was also found to be acceptable when compared to cellophane, although its membrane life was no greater than that of cellophane. It is therefore concluded that development of a membrane superior in all respects to both cellophane and the Nalco PVC is possible. Further development work in this area is strongly recommended, including the study of membrane characteristics to more clearly identify problem areas and eliminate present problem areas such as those caused by stress effects in the PVC membrane.

Tests are presently in progress on PVC and cellophane in which all stress effects have been eliminated. Five sheets of PVC and, as a control, one sheet of cellophane membrane were mounted in containers with a restraining screen positioned above the membrane. The containers were filled with urine and gravity fed through a calibrated burette. The restraining screen holds the membrane in place and prevents the urine pressure head from creating any stress effects on the membrane. The containers were placed in a hot water bath and the water vapor evaporated into the atmosphere. The quantity evaporated is measured periodically by the decrease in the level of the burette.

At this writing, the PVC membranes have processed 3.8 liters of water, equivalent to 300 lb/ft². The cellophane membrane has processed 3.6 liters, but has also passed a significant amount of solids.

United Aircraft Corporation Research Laboratories, who have had experience in fabricating membranes for fuel cell applications, are presently engaged in the development of a membrane that is hoped will surpass PVC in performance and endurance.

DESIGN STUDIES

Objectives

1. Establish concepts for a flight system considering:
 - a) Sterilization
 - b) Maintainability
 - c) Penalty
2. Optimization studies to determine the effect of varying:
 - a) Heater location
 - b) Recirculation flow rate
 - c) Diffusion gap width
 - d) Evaporating and condensing temperature
3. System comparison against other competitive water reclamation systems.

Discussion

The prime requirement for a water reclamation system is that it produces chemically pure and sterile water. Experience with a variety of evaporative-type systems has shown that achieving chemical purity is relatively easy; however, sterility requires special consideration and design provisions.

The vapor diffusion system is well suited to producing bacteria-free water once the system has been brought to a sterile condition. The membranes considered for use are absolute bacteria filters as demonstrated by test. With an originally clean condenser the condensate requires no further treatment or filtration to be acceptable for use, even though charcoal may be utilized to improve taste and odor. In the event of a membrane puncture the pressurized gap will force gas into the urine and prevent unprocessed liquid from reaching the condenser.

There is, however, always the possibility of an accidental event which may contaminate the system while in use. The design must therefore consider methods of in-flight cleaning and sterilization. The flight concept described below has provisions for maintenance and sterilization.

Flight System Description

The basic configuration for general application for a flight-type vapor diffusion water reclamation system as presently conceived is shown in fig. 20. In this system,

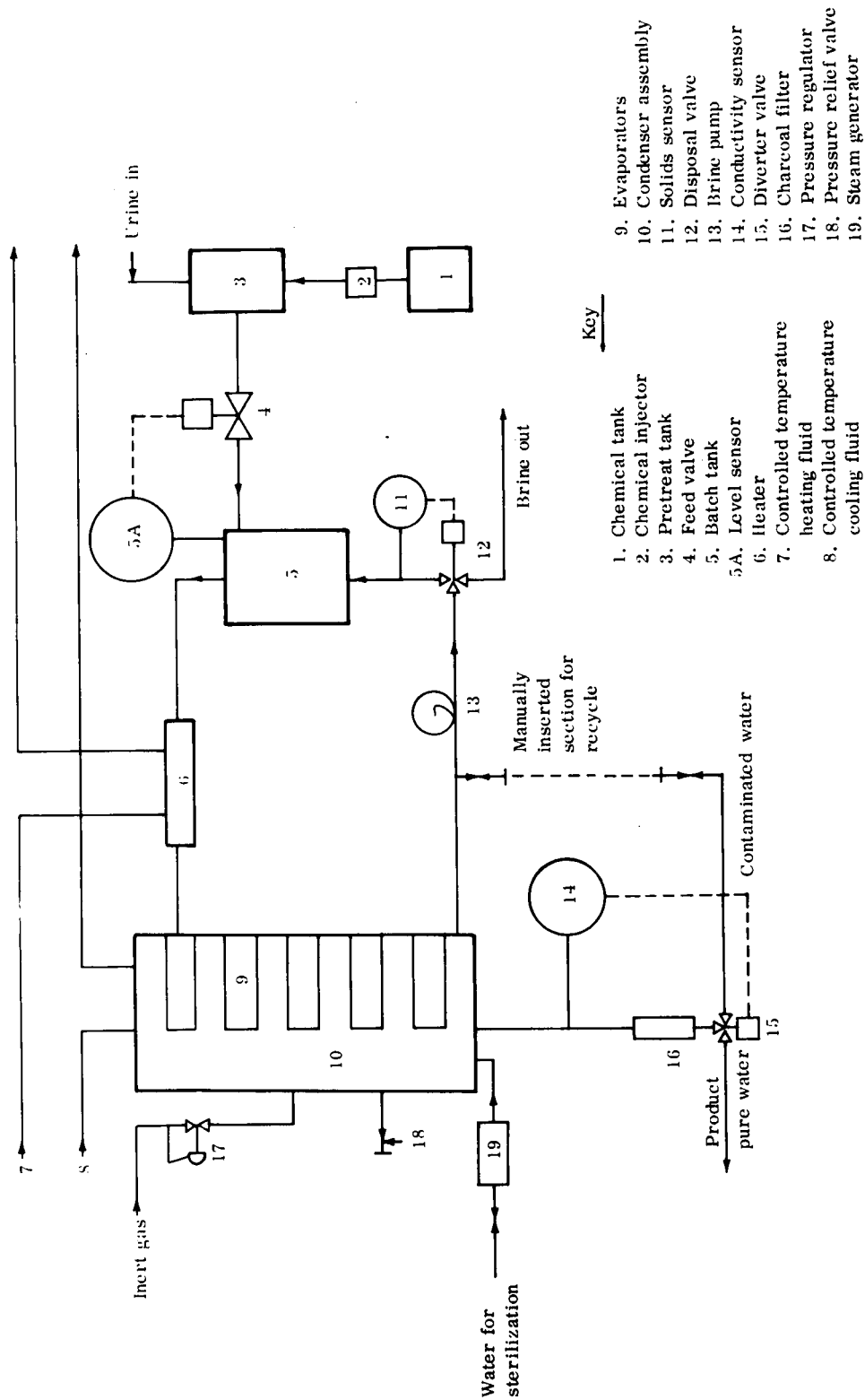


Figure 20. Flight Concept Vapor Diffusion Water Reclamation System

urine is collected in tank (3) and treated with chromic acid delivered from tank (1) by the chemical injector (2). It is fed automatically into the system through valve (4) on a signal from the batch tank quantity sensor (5A). A pump (13) circulates the solution through the batch tank (5), the heater (6), the evaporators (9), and the concentration sensor (11). If desired, a by-pass around the batch-tank could be used to reduce the start-up heat load of the system. However, if waste heat or a fixed power heat source is used there is no advantage to the vehicle to using a by-pass.

The system is supplied with heating fluid (7) and cooling fluid (8) from the vehicle. Pressure regulated (17) inert gas is used to pressurize the gap between the evaporator and condenser modules. Inert gas is also supplied to the batch tank which acts as an accumulator-regulator to maintain the proper differential between gap and urine pressure (urine slightly below gap). A relief valve (18) is provided to prevent over-pressurization in event of supply regulator failure.

The condensate is forced from the condenser (10) by gap pressure which can be up to 5 psia above ambient. No further pumping is needed if water is to be used and stored at 5 psia or less.

The condensate flows through the conductivity sensor (14), and the charcoal filter (16) to storage. A signal from the conductivity sensor, in the event of impure or poor quality product water, activates the solenoid valve (15), which goes to an isolated position, and at the same time triggers an alarm. A by-pass line is then manually attached to divert the processed water back to the batch tank. The by-pass line is not permanently attached, thus eliminating any path for back flow and resultant contamination.

A steam generator (19) is provided for in-flight sterilization of the system. The steam generated at a pressure above the porous plate capillary pressure would heat the entire assembly to sterilization temperatures. Both steam and condensate would flow through the water delivery circuit. It would be desirable to disconnect the delivery line and dump the steam and water into the vehicle humidity control system during sterilization.

Diffusion Still Assembly (fig. 21)

This component consists of a battery of rigidly mounted condenser modules alternating with gaps for the insertion of evaporator modules. The gaps contain inflatable seals which enclose and position the evaporators and establish the diffusion gap. Manifolds and valving for the fluid and gas flows required in the assembly are included. The condenser modules are removable for replacement, sterilization, or cleaning, if necessary.

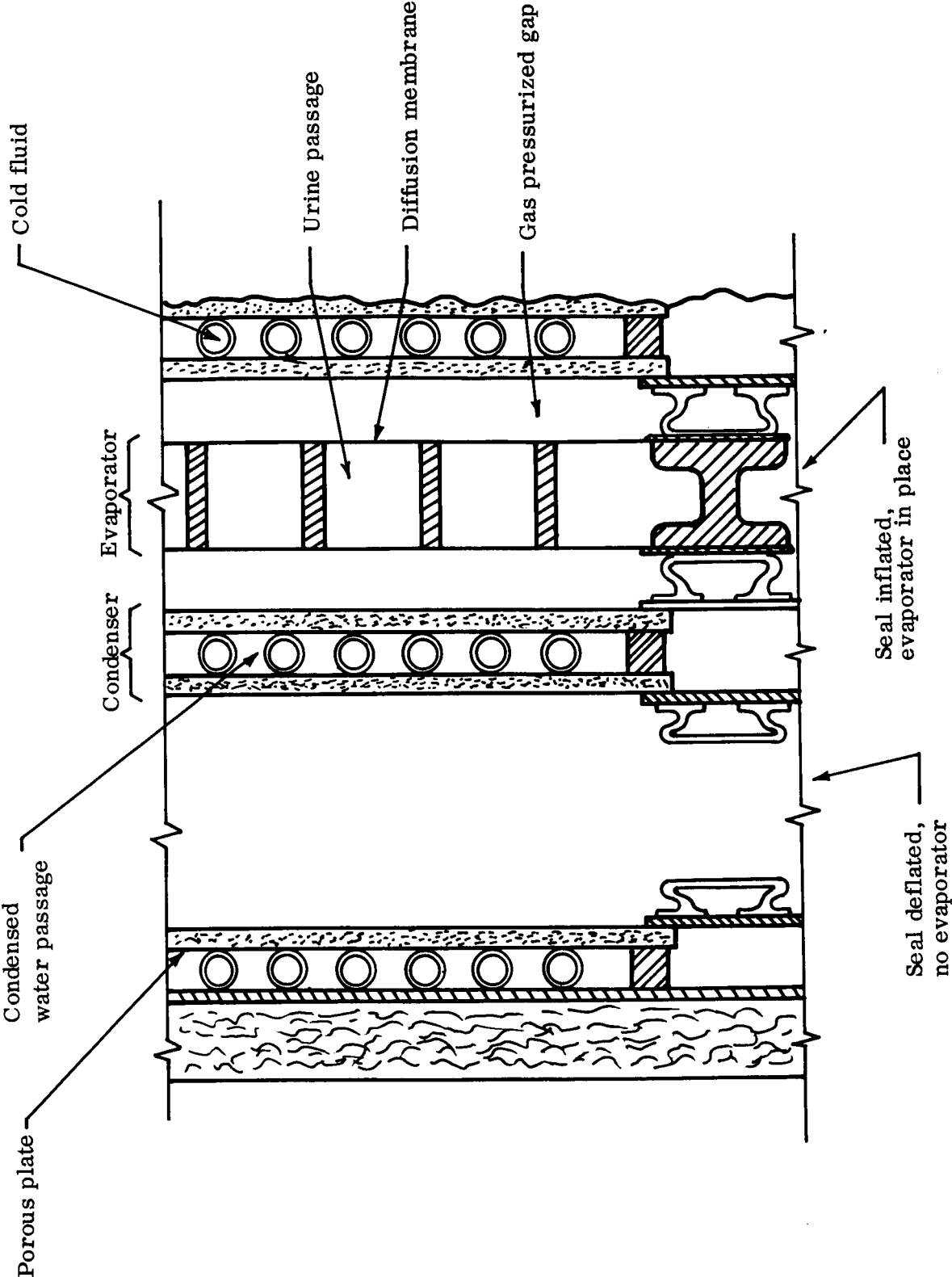


Figure 21. Prototype Diffusion Still Assembly

Condensers (figs. 22 and 23)

Each condenser module consists of a set of small diameter coolant tubes, headered at each end, sandwiched between two porous plates. The space between the tubes is the condensate passage. A frame connects the plates and provides mounting surfaces for the condensers in the still assembly and for the inflatable seals. Pressurized gas for the inflatable seals and the diffusion gap is introduced through ports in the frame.

The porous plate when wet acts as a seal to prevent vapor or gas from entering the condensate passage. This concept for condensation and separation of water from vapor is particularly well suited to the vapor diffusion unit. (a) The porous plate is exposed only to extremely pure filtered water and will not be clogged by foreign matter. (b) Presently available plates have water flow capacities greatly in excess of the membrane flow rate. (c) The use of non-corrosive metals allows high temperature sterilization and cleaning of the condensers and diffusion modules.

The porous plates in the prototype diffusion still have accumulated approximately 5,000 hr of operation with no performance degradation or failures.

A standard condenser module would be 8 in. x 8 in. and have 120 sq in. of active condenser area. Based on the use of 0.012-in. thick nickel plates a module would weigh 1.9 lb.

Evaporators (fig. 24)

An evaporator module consists of a plastic frame-flow path assembly with a membrane bonded to either side at all points of contact. Self-sealing quick disconnects provide for the circulation of urine to the evaporator. A standard evaporator module would contain 120 sq in. of active membrane, to match the condenser module, and would weigh 0.8 lb. The longest duration test to date processed 250 lb of water per sq ft of membrane area. Based on achieving twice this amount, through membrane development, an evaporator module would process 420 lb of urine before replacement.

To simplify evaporator design all heating is done external to the module. This eliminates the need for heat transfer surfaces and heating fluid flow through the evaporator.

Concentration Sensor

This component is presently in the "black box" stage of development. In its simplest form it would be merely a tank level sensor calibrated for volume changes corresponding to percent recovery. Alternate arrangements may make use of the change in specific gravity, refractive index, viscosity or conductivity of the concentrating brine to provide a drain-feed signal to the valving.

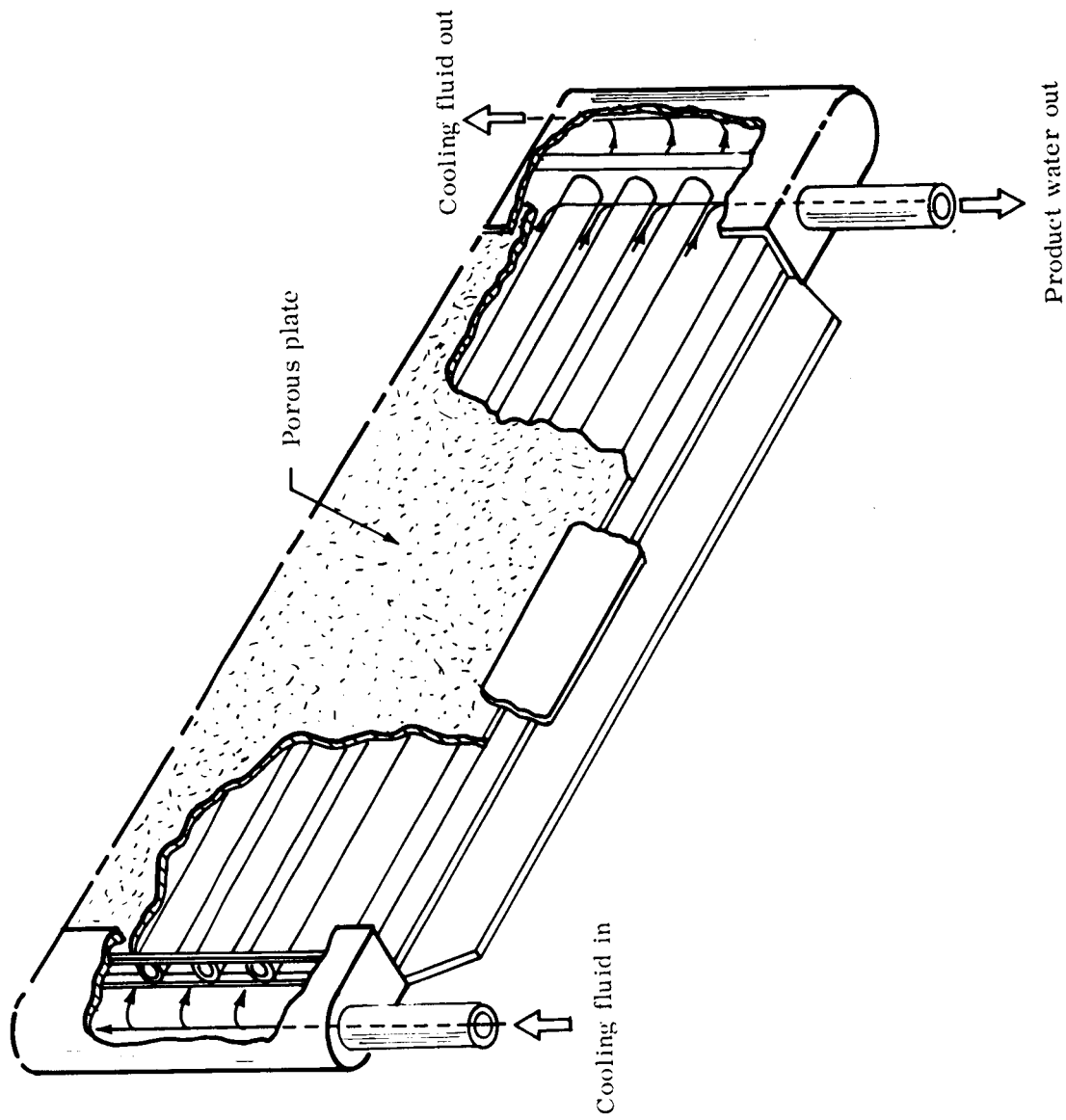
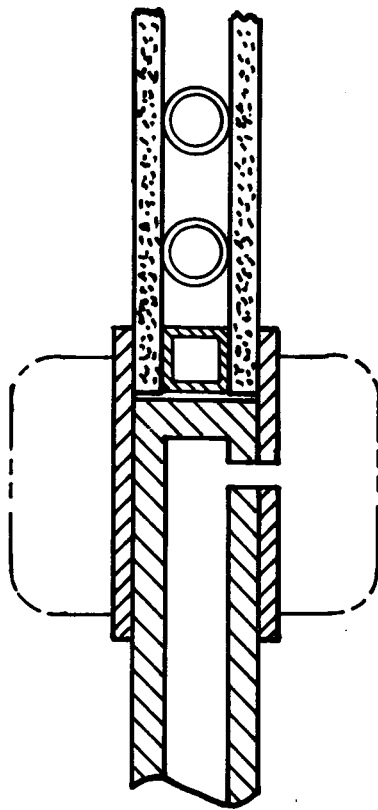
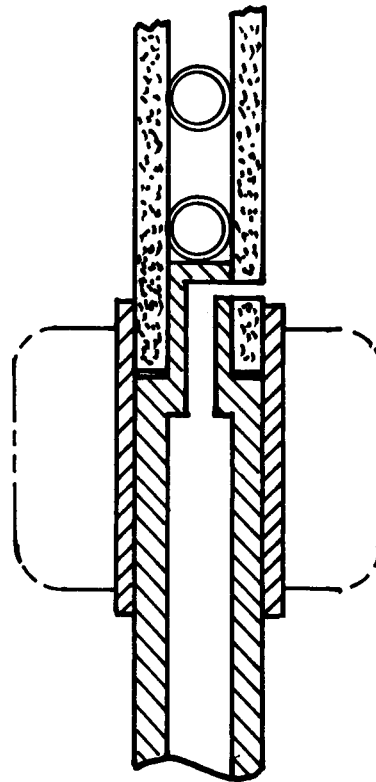


Figure 22. Prototype Condenser



Seal pressurization



Gap pressurization

Figure 23. Prototype Condenser Pressurization Arrangement

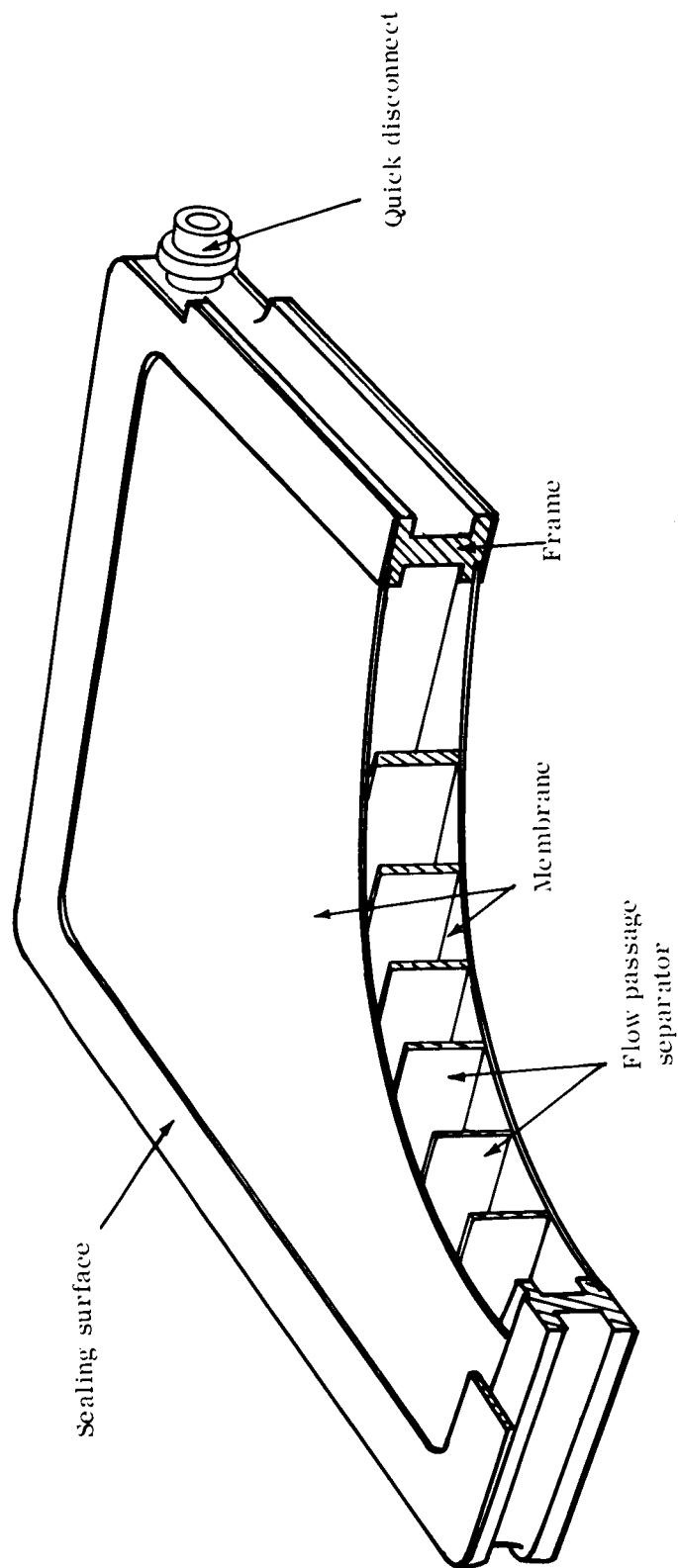


Figure 24. Prototype Evaporator

The remaining components of the system are present state-of-the-art. The heater would be of standard stainless steel plate for construction, and well insulated to prevent heat loss to ambient. The batch tank must also be insulated to prevent heat losses. A diaphragm pump would probably be best suited for the circulating loop.

Design Optimization

This section presents representative optimization studies. The actual design of a flight system requires detailed vehicle information such as available heating fluid flow rates and temperatures, total heat available, cooling fluid penalty etc. These studies were also based on developing a membrane that has the permeability of cellophane and a total flow capacity of 500 lb/ft². Both of these goals appear achievable with a reasonable membrane development program.

Heater location. - It is necessary to circulate flow through the evaporator to prevent a sludge build up on the membrane. A heat exchanger can be added to this recirculation loop, thus eliminating the need for heaters in the modules. The additional pumping power to provide heat transfer is negligible, being on the order of 1 or 2 W for a four-man system. An external heater also makes more efficient use of heat transfer surfaces, but since it is only a small percentage of the system weight this is not a major consideration.

A secondary heater could be used in the batch tank to reduce the start-up load on the system; however, this is a second order consideration and depends on the exact vehicle heating and cooling capabilities and penalty values.

A single heater in the recirculation loop is therefore recommended as being optimum.

Recirculation flow rate. - In all cases recirculation flow will be set by the system heat load. The flow must be great enough to prevent a large temperature drop across the evaporator. From fig. 14 on page 30 we see that performance is dependent of flow above some minimum to prevent sludge build-up. Heat transfer flow will always be above this minimum.

Operating parameters. - The optimization of diffusion gap width, condensing temperature and evaporating temperature interact because smaller gap widths and increasing temperature differences favor high mass transfer at the expense of greater heat transfer by conduction and radiation through the gas gap. The equations representing this are:

$$R = K_t A (p_2 - p_1)$$

$$Q = K_t A (T_2 - T_1)$$

$$\ln(p_2/p_1) = \frac{-\Delta H}{R_g} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

$$K_t = \frac{KA}{Z} + \delta A (T_2^4 - T_1^4)$$

where

K_t = total diffusion constant (experimental)

K_t = total heat transfer coefficient

ΔH = heat of vaporization of water

R_g = gas constant

δ = combined radiation constant

R = mass transfer rate through membrane

K = thermal conductivity of gas

A = membrane area

Z = gap width

T_2 = evaporating temperature

T_1 = condensing temperature

p_2 = pressure of water vapor at T_2

p_1 = pressure of water vapor at T_1

Any consistent units may be used. The equation must be slightly modified for boiling point elevation when high solids concentration is proposed in the evaporator.

A brief consideration of the above relationship shows that mass transfer is the best at the minimum gap width, the highest possible evaporating temperature, and the lowest possible condensing temperature. The condensing temperature effect, however, is considerably less significant than that of the gap width and evaporating temperature. Heat transfer is decreased by lowering the temperature difference, and to some extent by lowering the temperature level.

Diffusion gap width: Diffusion gap width is an optimization of heating-cooling load penalty versus system weight. Fig. 25 shows how required membrane surface

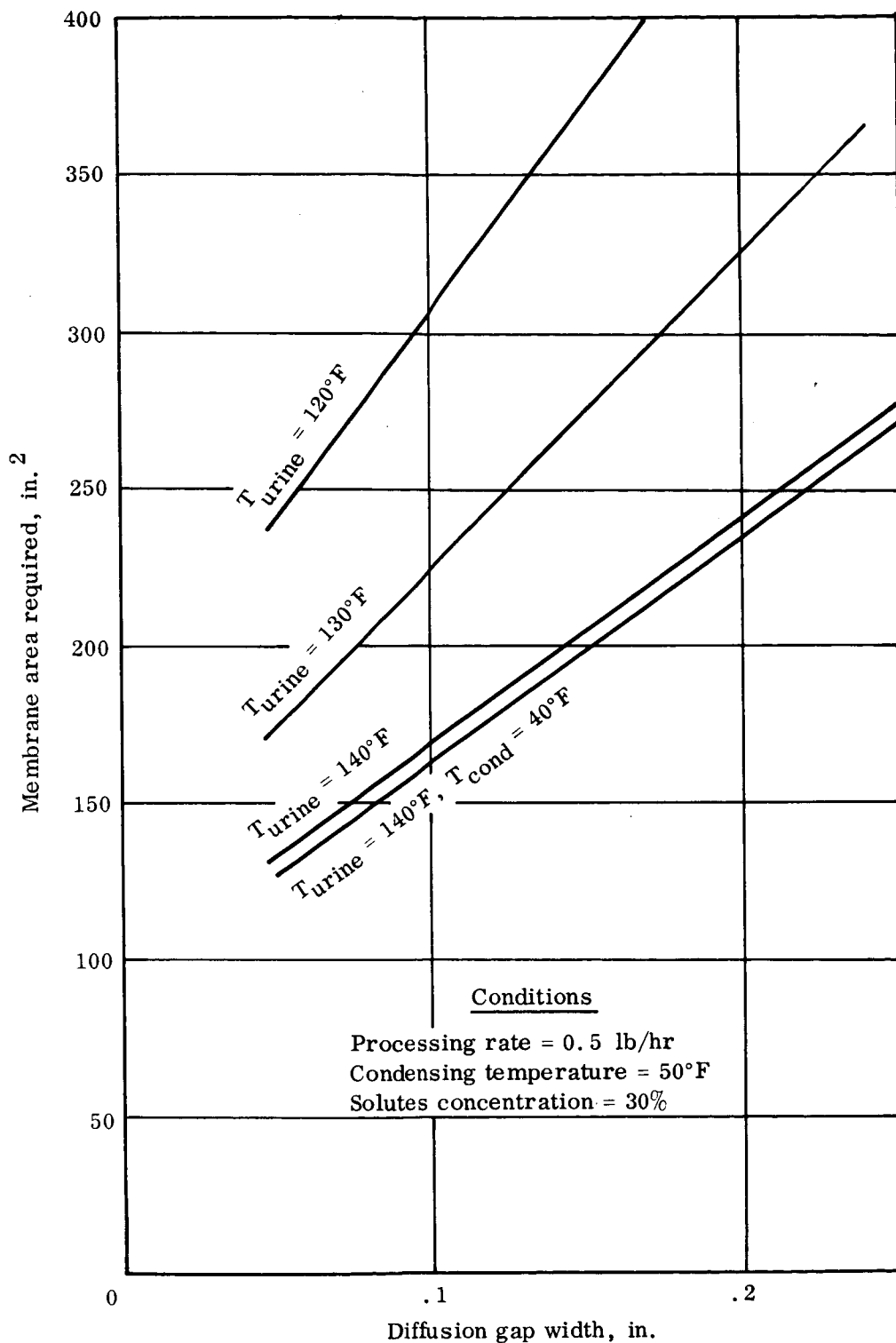


Figure 25. Membrane Area as a Function of Diffusion Gap Width for Specific Temperature Combinations

increases with diffusion gap width. Fig. 26 shows the decrease in heat losses with gap width. A representative penalty optimization is shown in tables VI, VII, and VIII. Table VI shows required evaporator area and Q loss for a unit operating at an evaporator temperature of 140°F, a condensing temperature of 50°F and a process rate of 0.5 lb/hr. Table VII is a comparison for a low heating-cooling penalty while table VIII is a comparison for a high heating-cooling penalty. In both cases a gap width of 0.1 in. is nearly optimum. This points out that gap width selection is relatively insensitive to the actual value assigned to heating-cooling penalty.

Optimization was done on a delta basis and assumed no change in the rest of the system. It was assumed that spare evaporators and condensers, equal to the number installed, were carried for reliability. The total number of evaporator modules carried is set by the total processed flow (see evaporator description) and not by process rate.

Evaporating temperature: A flight system must be designed for the available heating fluid temperatures. A practical VDR design is possible with heating temperatures from 150 down to 90°F.

As the temperature difference between evaporation and condensation decreases, heat losses per unit area decrease; however, the required area increases rapidly. As a result heat losses are greater at the low temperature differentials. Fig. 27 shows heat required per pound of water processed as a function of heating fluid temperature. At 150°F heating fluid the total heat required is a minimum of 1600 Btu/lb.

Condensing temperature: The vapor diffusion system must also be designed for the available cooling fluid temperature, likely to be 40-60°F. Higher temperatures are available by reducing coolant flow.

Large differences in evaporating and condensing temperatures brought about by lowering condensing temperature are not likely to increase partial pressure driving forces very much, but heat transfer can be increased considerably. The importance of heat transfer will be minimized in a practical case by the relatively large and constant required heat of vaporization and the probable use of waste heat. Fig. 28 shows the effect of changing condensing temperature at one evaporating temperature (140°F) upon area and heat requirements. It is seen that the system will be relatively insensitive to condensing temperature until above 90°F.

Optimization Conclusions

- A. A heater external to the evaporator module should be used.
- B. Brine recirculation rate should be selected to avoid appreciable temperature drop across the evaporator.

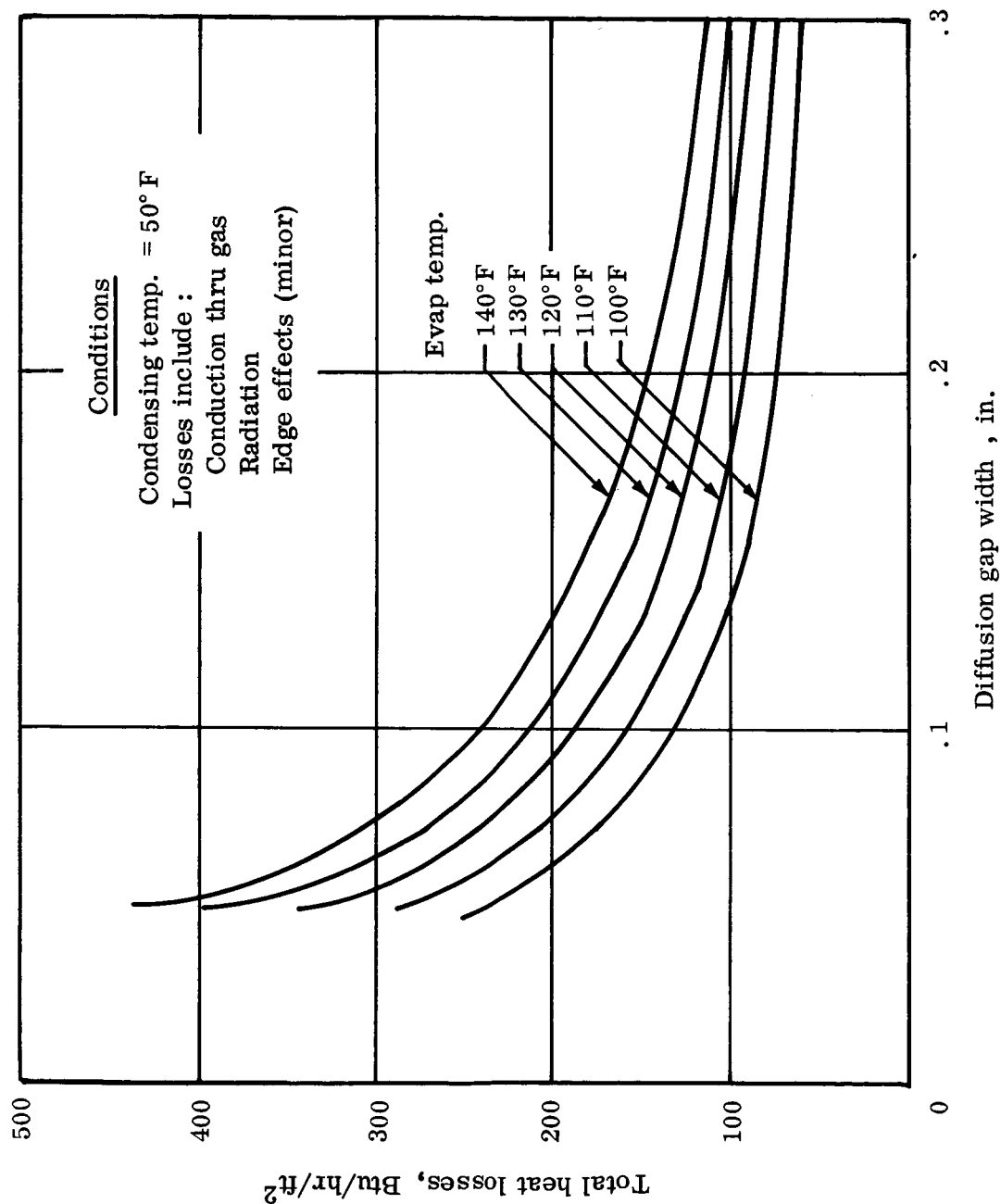


Figure 26. Total Losses as a Function of Diffusion Gap Width for Various Evaporating Temperatures

TABLE VI

DIFFUSION GAP WIDTH EFFECT ON EVAPORATOR AREA AND HEAT LOSS

W_{gap} -in.	$A_{\text{evap.}}$ -in. ²	Q_{loss} - Btu/hr.
0.05	135	409
0.1	170	286
0.15	205	250
0.2	241	243
For $T_{\text{Urine}} = 140^{\circ}\text{F}$ $T_{\text{Cond.}} = 50^{\circ}\text{F}$ $W_{\text{H}_2\text{O}} = 0.5 \text{ lb/hr}$		

TABLE VII

TOTAL PENALTY FOR VARIOUS GAP WIDTHS
FOR A LOW HEATING - COOLING PENALTY

W_{gap}	Δ Fixed weight	$Q \times 0.015$	Total penalty
0.05	5.17	6.13	11.3
0.1	6.52	4.30	10.82 ← Min.
0.15	7.86	3.75	11.61
0.2	9.25	3.64	12.89
Penalty $Q = 0.015 \text{ lb/Btu/hr}$			

TABLE VIII

TOTAL PENALTY FOR VARIOUS GAP WIDTHS
FOR A HIGH HEATING - COOLING PENALTY

W_{gap}	Δ Fixed weight	$Q \times 0.015$	Total penalty
0.05	5.7	20.4	26.1
0.1	6.52	14.3	20.8 ← Min.
0.15	7.86	12.5	20.36
0.2	9.25	12.1	21.35
Penalty $Q = 0.05 \text{ lb/Btu/hr}$			

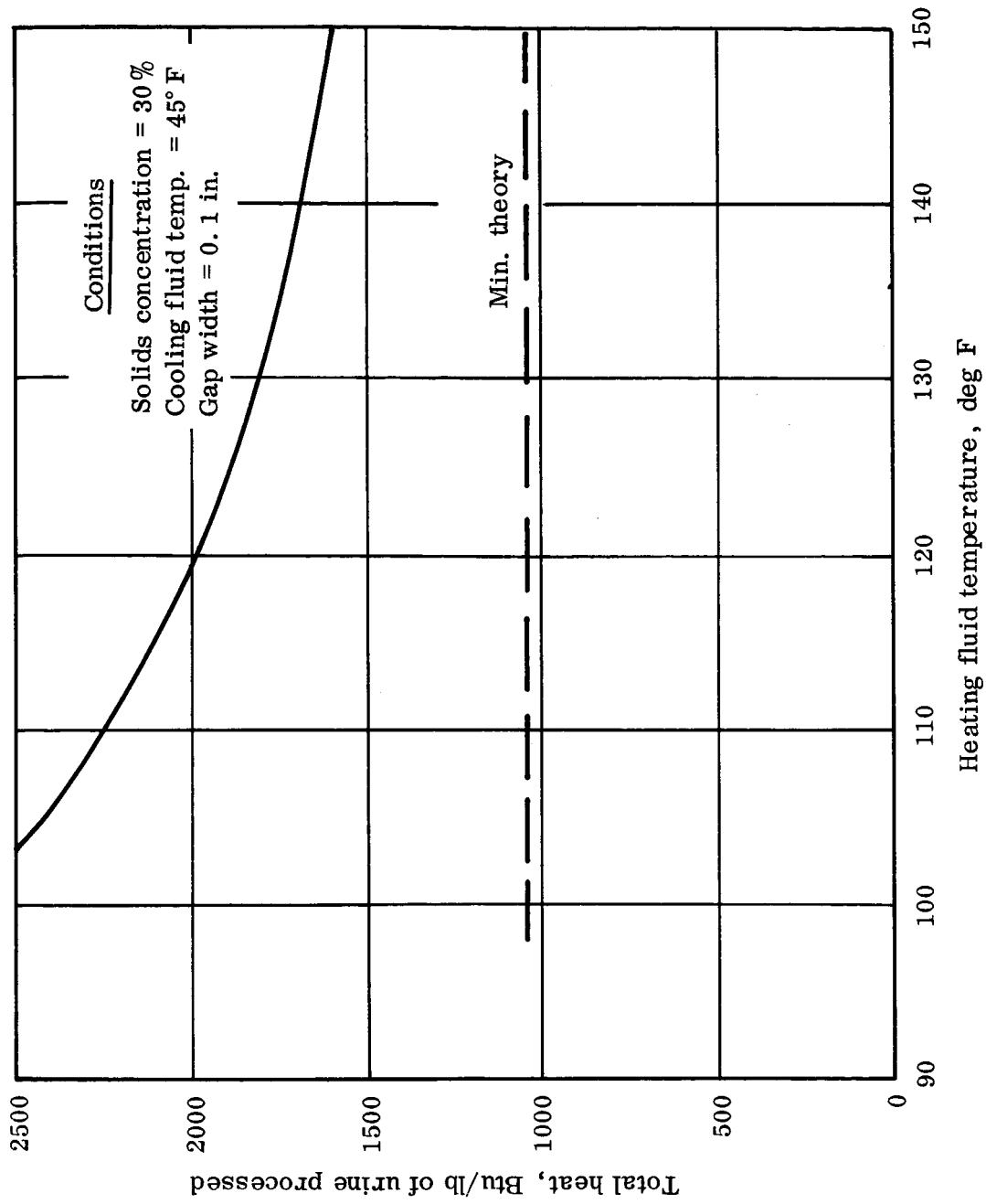


Figure 27. Total Heat Required as a Function of Heating Fluid Temperature

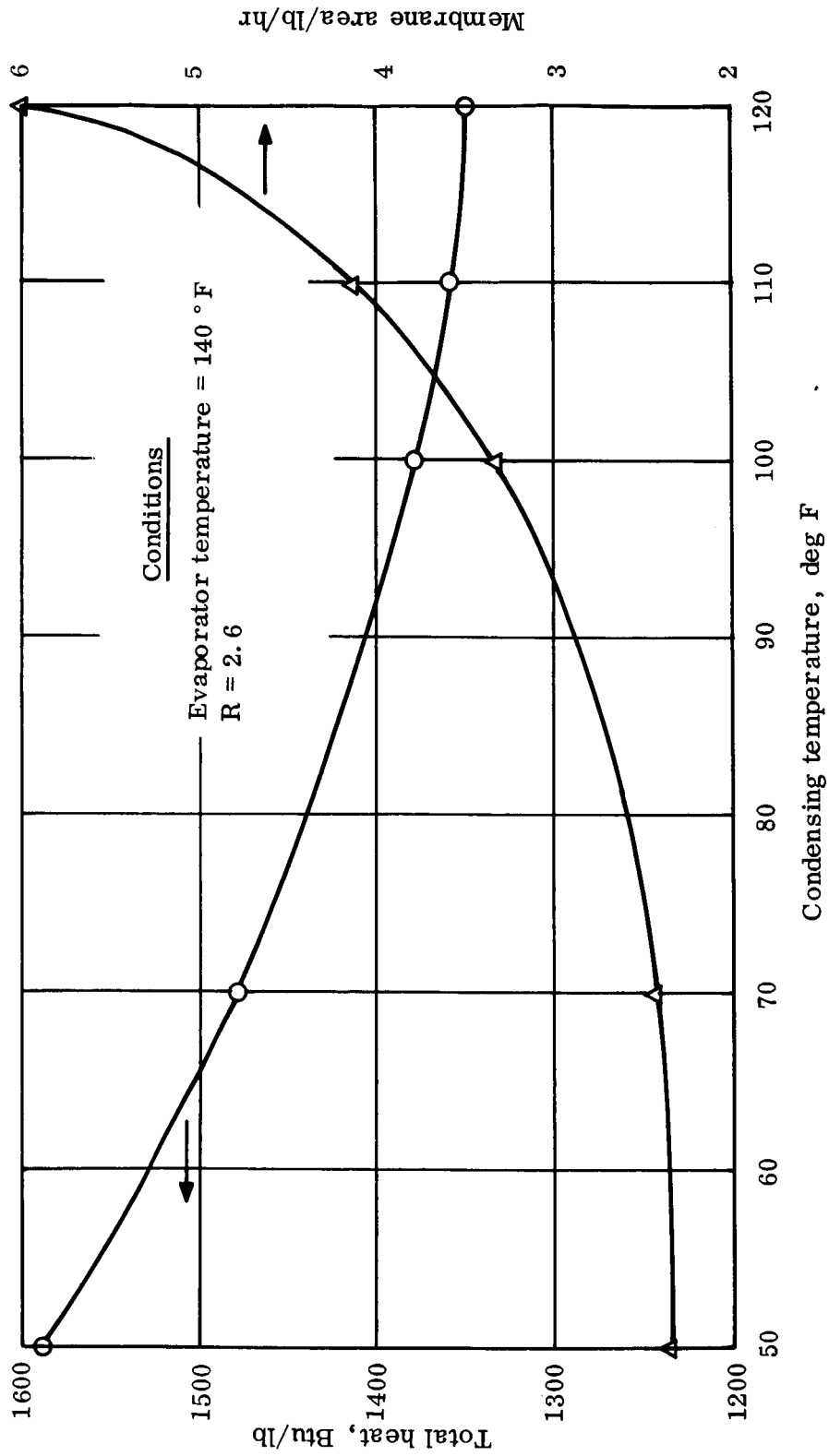


Figure 28. Total Heat and Membrane Area as a Function of Condensing Temperature

- C. A diffusion gap of 0.1 in. will be nearly optimum for a large range of conditions.
- D. The highest possible heating fluid temperature (up to 150°F) should be used.
- E. Condensing temperature is relatively unimportant and will be adequate in any realistic design.
- F. The VDR is relatively insensitive to parameter changes in a design optimization study.

System Comparison

This section presents the flight weights and penalties for four system design points. This information allows evaluation and comparison of the VDR with other water reclamation systems. The design points chosen are a 4 man and a 9 man system for both waste heat temperatures of 150°F and 105°F.

Ground Rules

The following ground rules were used for making system weight estimates.

1. 500 day mission - no resupply
2. 3.3 lb of urine/man day
3. Spares to achieve 0.9999 mission reliability
4. A membrane permeability equal to that achieved with cellophane.
5. A total membrane flow capacity of 500 lb/ft².
6. Standard 8 in. x 8 in. evaporator and condenser modules used for all designs.
7. Water recovery of 95%.
8. Design safety factor = 20% minimum on process rate.

System Design

Table IX shows a detailed weight breakdown of a system designed for four man 95% - recovery, a heating fluid temperature of 150°F, and a cooling fluid temperature of 45°F.

The number of standard modules required to meet this requirement is 1.42, therefore 2 were used providing 40% process rate factor of safety. The weight breakdown shows installed weight, spares required to achieve basic performance, and weight of additional spares required to achieve the 0.9999 mission reliability. These weights include all expendables such as pre-treat chemical.

TABLE IX

VAPOR DIFFUSION WATER RECLAMATION SYSTEM
WEIGHT AND VOLUME ESTIMATES

Item	Quantity			Weight - lb			Volume cu-in.	
	Installed	Perf. spares	Rel. spares	Installed	Perf. spares	Rel. spares	Installed	Spares
1 Pre-treat & tankage	1	3	1	10.6	31.8	10.6	160	1200 ¹
2 Chemical injector	1	0	2	0.75	-	1.5	-	-
3 Collection tank	1	0	0	13.1	0	0	540	-
4 Supply valve	1	0	1	0.25	0	0.25	-	-
5 Batch tank	1	0	0	8.7	0	0	400	-
6 Heater	1	0	0	3.0	0	0	-	-
9 Evap. modules	2	14	4	1.6	11.2	3.2	-	360
10 Condenser modules	2	2	2	3.8	0	3.8	350	20
11 Concentration sensor	1	0	1	0.5	0	0.5	-	-
12 Waste removal valve	1	0	1	0.36	0	0.36	-	-
13 Recirculation pump	1	0	2	1.50	0	3.00	-	-
14 Conductivity sensor	1	0	1	0.35	0	0.35	-	-
15 Diverter valve	1	0	1	0.35	0	0.35	-	-
16 Charcoal	1	19	0	0.40	7.6	0	-	-
17 Pressure regulator	1	0	1	0.5	0	0.5	-	-
18 Pressure relief-valve	1	0	1	0.35	0	0.35	-	-
19 Steam generator	1	0	0	2.00	0	0	-	-
Other ²	-	-	-	12.00	0	0	750	-
TOTAL				60.11	50.6	24.77	2200	1900

¹Includes 50% storage packing density²Includes frame, insulation, plumbing, etc.

Process rate = 13.2 lb urine/day (20 hr/day operations)

Recovery = 95%

500 day mission - no resupply

T heating fluid = 150°F

T cooling fluid = 45°F

The spares required for reliability, including an extra tank of pre-treatment, are only 23% of the basic system weight. This number is fairly low because of the small size of the non-passive components.

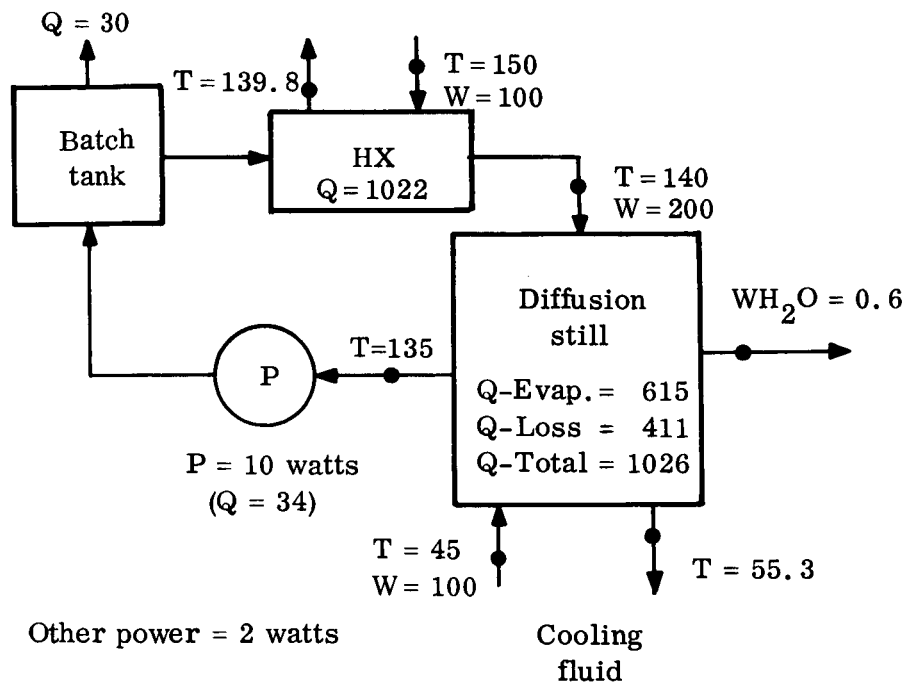
The system volume, including an allowance for packaging density, is 2200 cu in. This includes the collection tank. The envelope to contain the system would be approximately 10 in. x 11 in. x 20 in. The volume required for spares is 1900 cu in. The spares could be contained in a 10 in. x 10 in. x 19 in. space.

Fig. 29 shows a flow chart for this design. The system heating and cooling loads are 1026 Btu/hour and the power required is 12 W. Approximately 100 lb/hr of both heating and cooling fluid are required (assuming a c_p of 1).

Table X shows a weight and penalty summary for four system design points. The weights include all the items shown in table IX. For a fixed process rate spare weight goes down as the fixed weight goes up. This is because more evaporators are installed and evaporator replacement time is increased.

TABLE X
SYSTEM WEIGHT AND PENALTY SUMMARY
500 DAY MISSION - NO RESUPPLY

Number of men	4	4	9	9
Urine process rate-lb/day	13.2	13.2	30	30
Heating fluid temperature-°F	150	105	150	105
Cooling fluid temperature-°F	45	45	45	45
Heating & cooling load-Btu/hr	1026	1500	2330	3370
Power - W	12	12	17	17
Installed weight-lb	60	77	83	118
Spares weight-lb	76	74	154	151
Total weight	136	151	237	269
Cooling Penalty-lb	10.3	15.0	23.3	33.2
Heating penalty-lb	5.2	7.5	11.7	16.8
Power penalty-lb	3.6	3.6	5.1	5.1
Total penalty-lb	155.1	177.0	277.1	324.6
Evaporator replacement time-days	70	270	70	270



T = Temperature, °F
 W = Flow rate, lb/hr
 Q = Btu/hr

Figure 29. Four Man System Performance Flow Chart

Table XI shows this information reduced to lb/man for both fixed weight, expendable weight, and penalty. For this comparison, the basic weight does not contain installed expendables unlike the base weight in table X. The weight of the collection tank is also subtracted to make this data comparable to other published data. The system fixed weight varies substantially with design parameters; however, the time dependent weight remains nearly constant at about 0.04 lb/man day.

TABLE XI

SYSTEM WEIGHT AND PENALTY SUMMARY

Number of men	4	4	9	9
T heating fluid - °F	150	105	150	105
T cooling fluid - °F	45	45	45	45
Base fixed wt-lb/man*	9.0	13.2	5.1	9.0
Base penalty - lb/man**	4.8	6.5	4.5	6.2
Total penalty - lb/man	13.8	19.7	9.6	15.2
Time dependent wt-lb/man day	0.0435	0.042	0.0395	0.039
Additional penalty for less than 100% recovery-lb/man day	0.154	0.154	0.154	0.154

* Does not include collection tank

** Penalties

Cooling	= 0.01 lb/Btu/hr
Heating	= 0.005 lb/Btu/hr
Power	= 300 lb/kw

Based on 20 hr/day operation

The following table compares VDR with five other urine reclamation systems discussed in a report by V. Collins and D. Popma (ref. 5).

System	A	B	C	D	E	VDR
Base wt. (lb)	19.71	18.35	7.95	24.88	10.16	5.1
Time dep. wt. (lb/day)	0.31	0.08	0.11	0.69	0.52	0.2
Sizing factor (men)	3	8	15	5	13	9
Recovery efficiency (%)	90	99	97	86	91	95
Recovery cost (W-hr/lb)	292	66	38	142	28	12

- A Distillation with pyrolysis
- B Air evaporation
- C Vapor compression distillation
- D Reverse osmosis
- E Electrodialysis

The VDR ranks first in fixed weight and third in the most important factor, which is time dependent weight. The major portion of the time dependent weight of the VDR is the penalty for less than 100% recovery of available water. It should be pointed out that the VDR weights include reliability spares while the other systems do not appear to. If the recovery efficiency of the VDR were raised to 98% it would rank close to first in all categories.

Growth Potential

Recovery efficiency. - For medium duration mission of up to 200 days stored O₂ will be used and recovery efficiencies over 95% are not required. For these applications, the VDR in its present concept is ideal. For longer duration missions 100% recovery of available water is desirable. The present VDR system has recovered as high as 98% of available water during test. This was achieved because the batch tank acted as a settling tank for solids as they precipitated out of solution. Solids as they formed in the evaporator were washed out and did not interfere with performance. For Zero-G a filter or centrifuge in the recirculation loop could be used to remove the solids. This would enable the VDR to achieve over 98% recovery.

Reduction of expendables. - The pre-treat and tankage compose the major expendables for the VDR. These could be reduced by two methods:

- a) Operation at lower temperatures to prevent urea decomposition.
- b) The use of electrolytic pre-treatment.

Alternate use. - The probability of having waste heat available in the 100 to 150°F range is quite high. However, in the event that it becomes necessary to limit heat usage the VDR concept could be used for a vapor compression system. A schematic of such a system is shown on the following page.

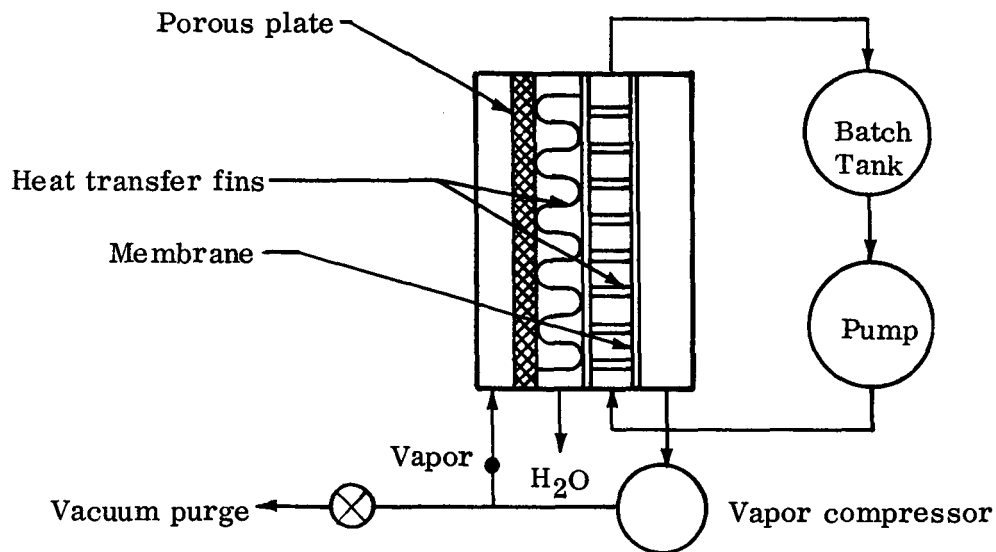


Fig. 30 shows compressor power versus membrane area for such a system. About 4 sq ft of membrane area and 55 W of power would be sufficient to produce water at the rate of one lb/hr.

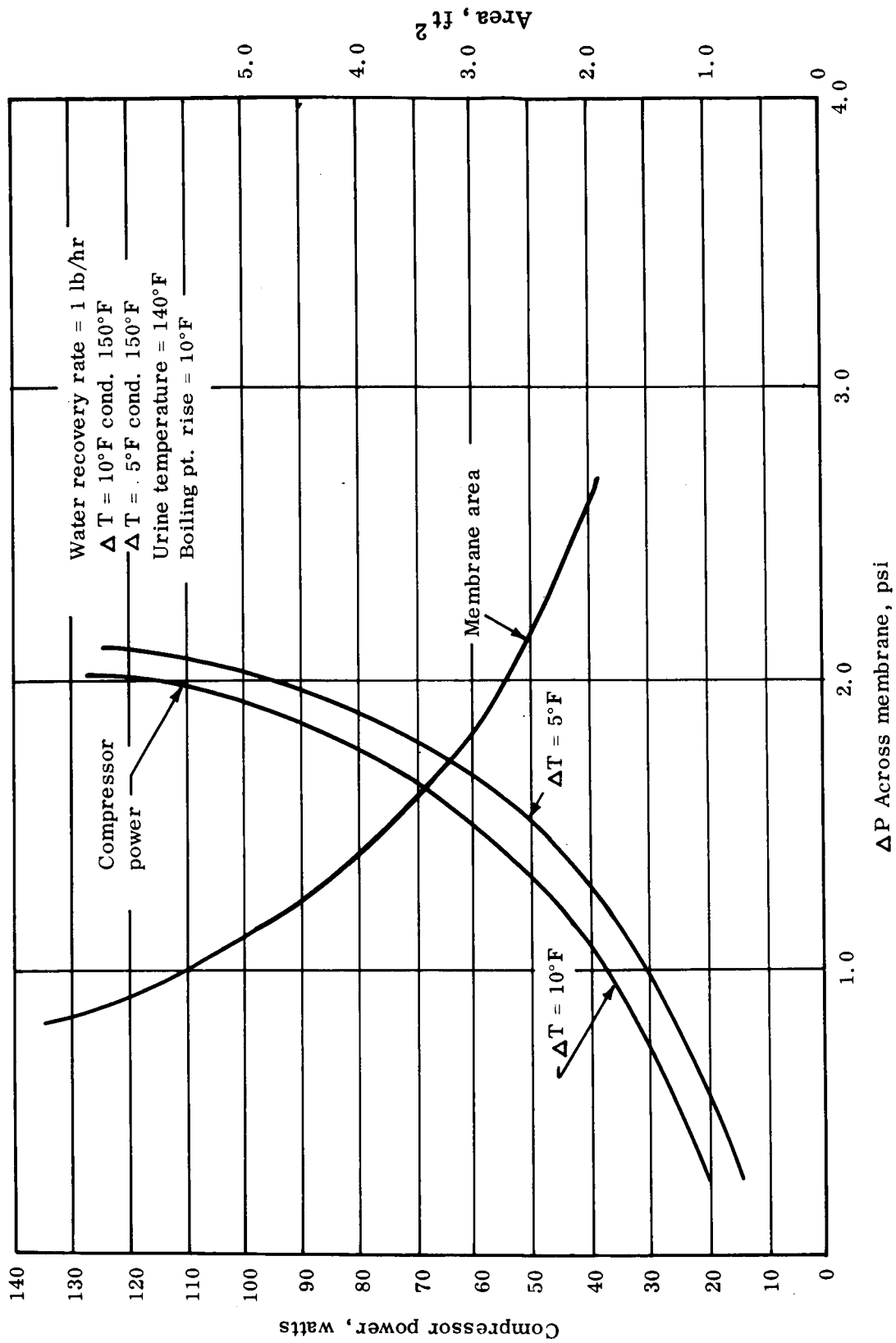


Figure 30. Compressor Power as a Function of Membrane Area

SAMPLE CALCULATIONS

For each of the test runs listed in table II, calculations were made to determine the actual evaporating temperature and the diffusion coefficients for the diffusion gap and the total system.

The basic data:

- R = water processed, lb/hr
- F = urine flow rate, lb/hr
- ΔT_e = temperature change of urine in evaporator, °F
- T_c = condensing temperature, °F

were used to determine:

- Q_s = sensible heat input to urine, Btu/hr
- Q_L = latent heat input to urine, Btu/hr
- Q_T = total heat input to urine, Btu/hr
- T_e = average evaporating temperature, °F
- p_1 = water vapor partial pressure at T_e , psi
- p_3 = water vapor partial pressure at T_c , psi
- K_m = membrane diffusion coefficient, lb/hr-ft²-psi
- K_g = gap diffusion coefficient, lb/hr-ft²-psi
- K_t = total diffusion coefficient, lb/hr-ft²-psi

Constant for all runs were:

- A = membrane and porous plate area, 0.792 ft²
- P_a = atmospheric pressure, 14.7 psia

A typical calculation is shown below. (Run 23)

$$\begin{aligned} Q_s &= FC_p \Delta T_e = 26.5 \times 10 = 265 \text{ Btu/hr} \\ Q_L &= Rhfg = 0.364 \times 1015 = 370 \text{ Btu/hr} \\ Q_T &= Q_s + Q_L = 635 \text{ Btu/hr} \end{aligned}$$

To determine T_e , these values of Q_L and Q_T were plotted (fig. 31) versus ΔT_e for the case of complete sensible heating with no evaporation (dotted lines). This straight line plot was used to approximate the actual case of simultaneous sensible and latent heating (solid line) and this plot used to determine the average temperature

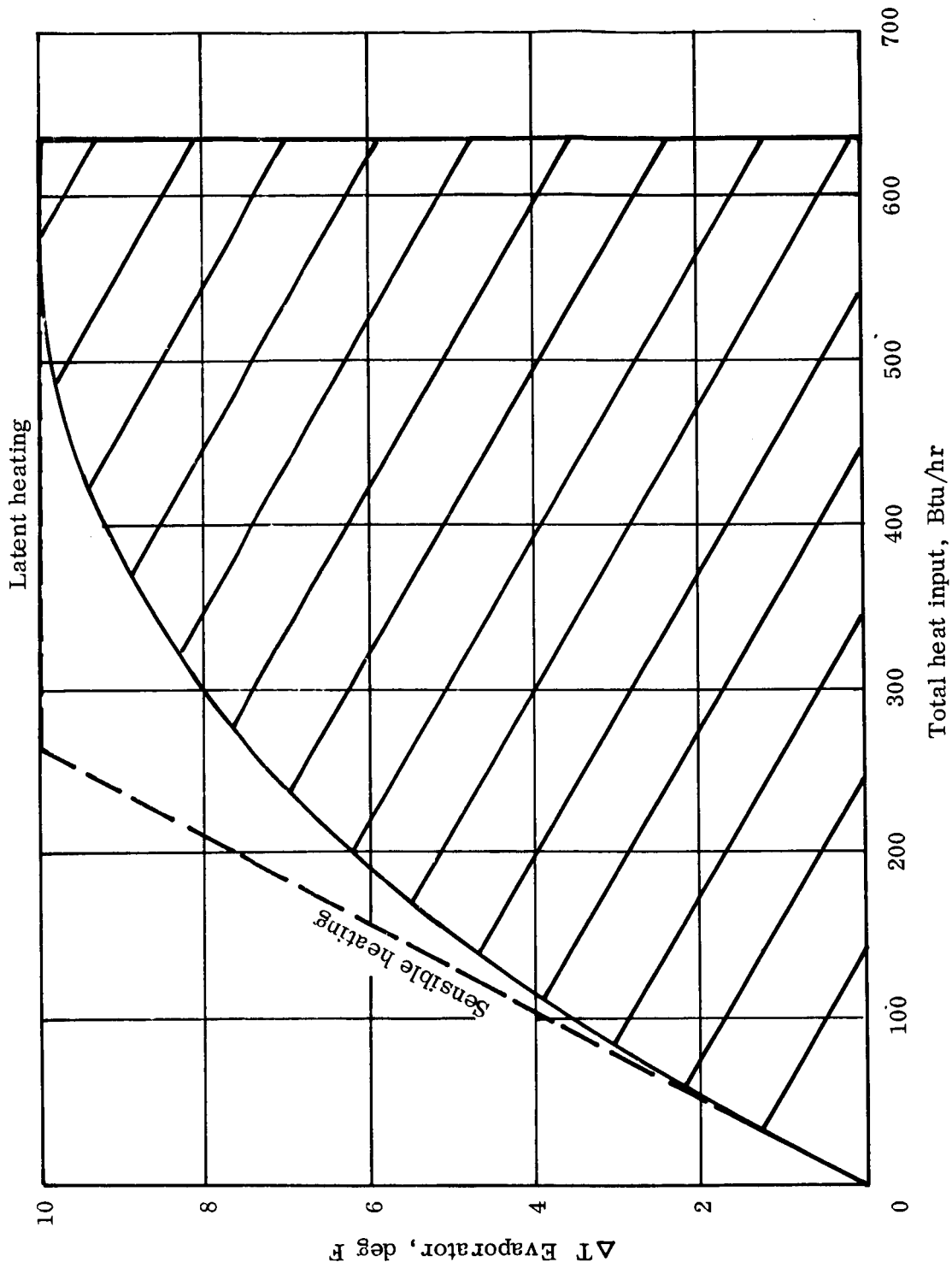


Figure 31. Evaporator Differential Temperature as a Function of Total Heat

in the evaporation (T_{ea}) by dividing the area under the curve by the total heat input, Q_T . T_e is the sum of this average and the evaporator inlet temperature. For Run 23, $A = 4250$, $T_{ea} = 6.7^\circ\text{F}$ and $T_e = 138.7^\circ\text{F}$.

The partial pressure of the water vapor in the urine at T_e is a function of the solids concentration of the urine. A plot of partial pressure versus urine temperature for various solids concentrations is shown in fig. 32, drawn from experimentally determined Duhring lines (ref. 6). The solids concentration is a function of the measured specific gravity of the urine, plotted in fig. 33. For Run 23, the measured specific gravity of 1.05 indicates a solids concentration of 12%. At $T_e = 138.7^\circ\text{F}$, this concentration indicates a p_1 of 2.80 psi. Water vapor partial pressures for various condensing temperatures are plotted in fig. 34. For Run 23, a condensing temperature of 69°F indicates a p_3 of 0.35 psi.

The total diffusion coefficient,

$$K_t = \frac{W}{A (p_1 - p_3)} = \frac{0.364}{0.792 (2.45)} = 0.188 \frac{\text{lb}}{\text{hr ft}^2 \text{ psi}}$$

The theoretical value of K_t was calculated by first calculating the theoretical K_g in

$$K_g \text{ theo} = \frac{D P_t M}{R_o T Z P_{gm}} = 0.305 \frac{\text{lb}}{\text{hr ft}^2 \text{ psi}}$$

and using this value with the value of $K_m = 0.323 \frac{\text{lb}}{\text{hr ft}^2 \text{ psi}}$ determined in Runs 21-23 in

$$\frac{1}{K_t \text{ theo}} = \frac{1}{K_g \text{ theo}} + \frac{1}{K_m} = \frac{1}{0.305} + \frac{1}{0.323} = 3.28 + 3.10$$

$$K_t \text{ theo} = \frac{1}{6.38} = 0.157$$

Hamilton Standard

Division of United Aircraft

Windsor Locks, Connecticut, July 19, 1968

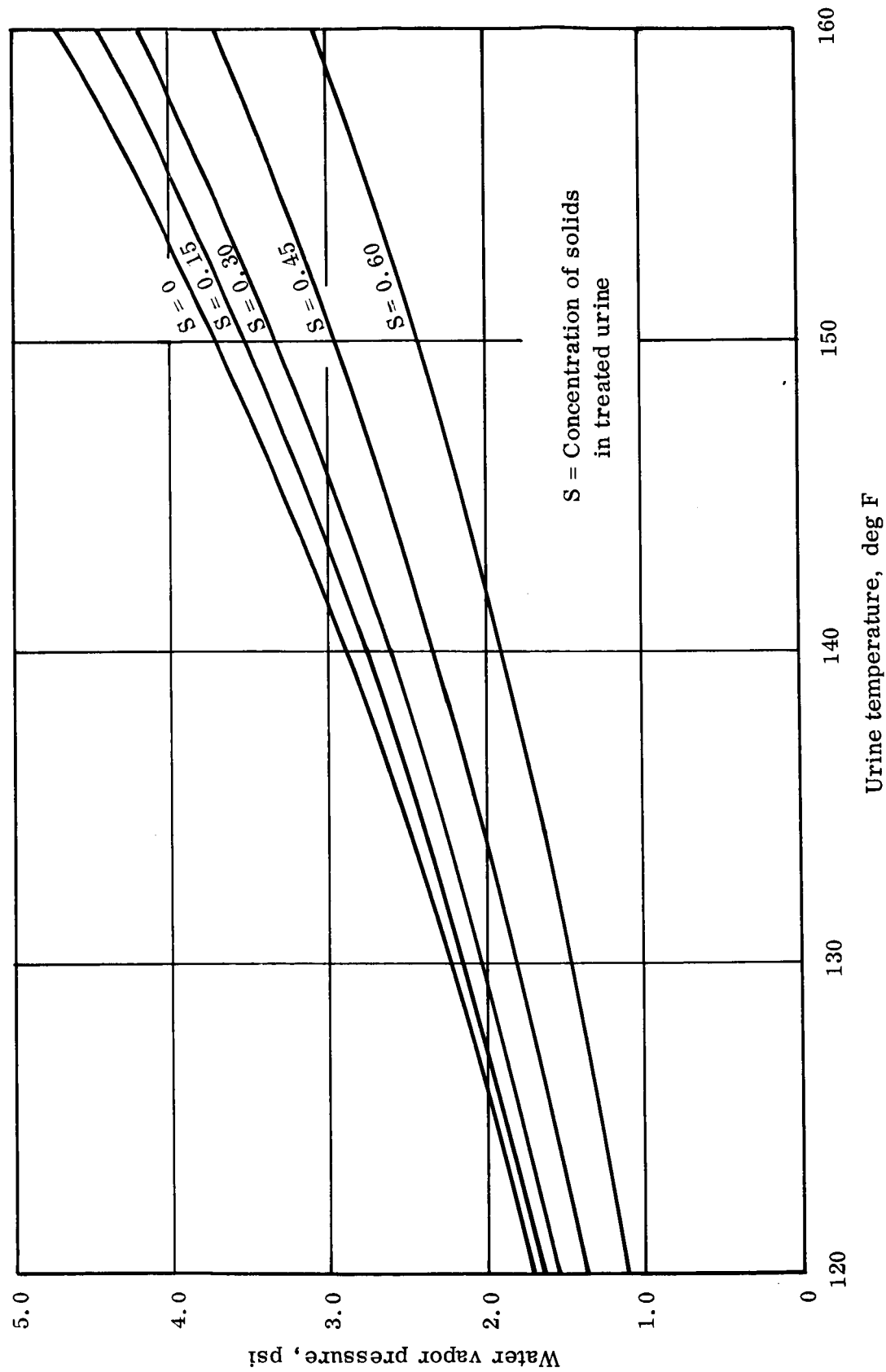


Figure 32. Water Vapor Pressure as a Function of Urine Temperature for Specific Solids Concentrations

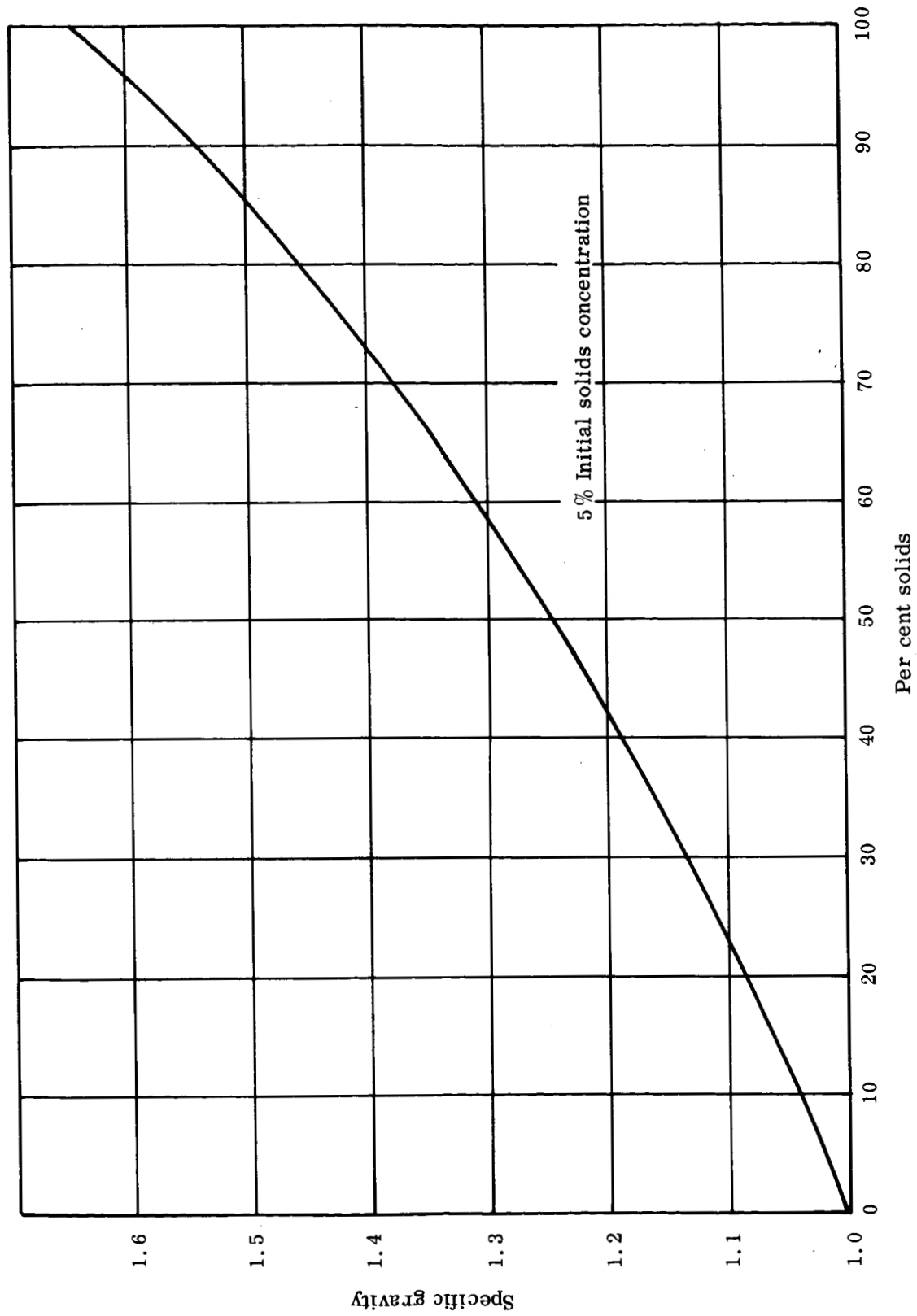


Figure 33. Specific Gravity of Urine as a Function of Solids Concentration

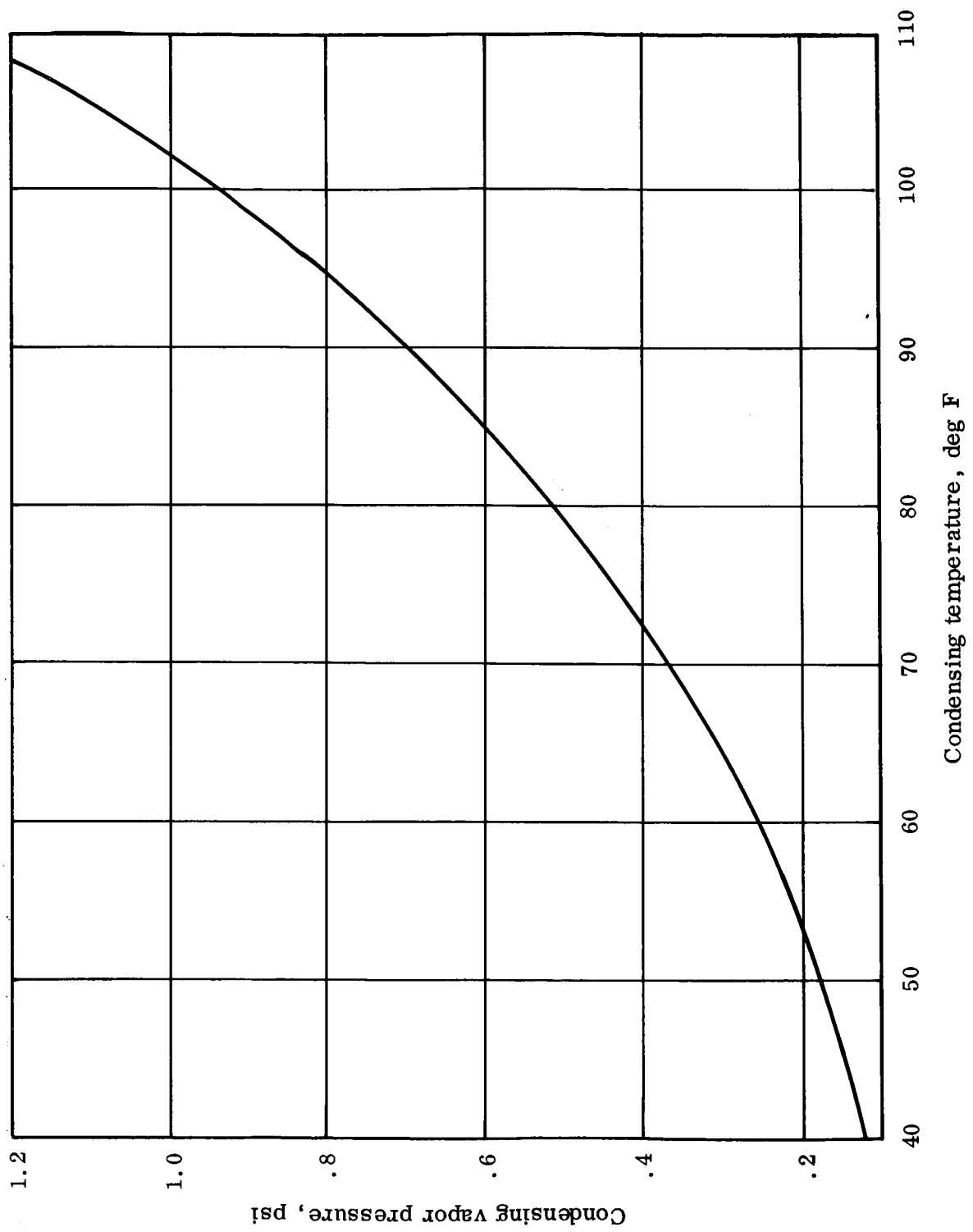


Figure 34. Saturated Vapor Pressure as a Function of Condensing Temperature

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